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Abstract

After defining NDT and comparing this concept with destructive testing, a short description is given of NDT methods other than radiologic. Basic concepts of radiologic methods are discussed and principles of radiography are explained. Radiation sources and gamma radiography machines are next reviewed and radiographic inspection of weldings and castings is described. A brief description is given of the radiographic darkroom and accessories. Other radioisotope methods, such as neutron radiography are shortly reviewed. The presentation is concluded by cost estimations for the radioisotopic equipment.

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ON
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BHABHA ATOMIC RESEARCH CENTRE
BOMBAY - INDIA

RADIOISOTOPES IN NON-DESTRUCTIVE TESTING

Review of Applications

by

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Text of paper presented at the IAEA Advisory Committee Meeting on Industrial Appæications of Radioisotopes, held in India on 13-17 December, 1976. The participants of the meeting were from:

- Bangla Desh
- India
- Indonesia
- Malaysia
- South Korea
- Thailand

At the meeting invited papers were presented by following experts:

- J. Cameron (UK)
- C.G. Clayton (UK)
- J.C. Domanus (Denmark)
- M. Kato (Japan)
- J.R. Puig (France)

This is the full text of the Danish paper.

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1. INTRODUCTION

Non-destructive testing (NDT) plays an important role in most quality assurance (QA) programs for different industrial products. NDT is useful for quality control (QC) not only of the finished products, but also of the raw materials as well as half-finished products. NDT can be used at all stages of production to control quality. NDT helps not only to maintain the prescribed quality during the established production process, but is also used during the process of establishing a new technology for improving the product quality or for developing a new product. Outside the manufacturing field, NDT is also widely used for routine or periodic control of various items during operation to ascertain that their quality has not deteriotated with use.

Requirements to apply NDT may originate not only from the manufacturer of a certain product, who by applying adequate QA and QC methods keeps his products at a high quality level, but can be prescribed also by supervising authorities, who wish to assure , that the particular product will be a danger to its users, to the general public, or to the environment through performance failure.

2. WHAT IS NDT?

The term "Non-destructive testing" is used to describe the material testing methods that, without damaging or influencing the usefulness of the material, give information about its properties. NDT is concerned with revealing all sources of weakness of an item under inspection other than those associated with its design. NDT is not generally concerned with decisions as to whether or not the item is fit for a particular application, because it is not so much the mere presence of a particular defect that must be taken into account on deciding on acceptance or rejection. It is rather the presence of the defect in relation to such other factors as position, size, other imperfections, if any, in the adjacent material, the mechanical properties of the basic material, and the service conditions of the item as a whole.

The primary duty of anyone conduction NDT is to supply as much detailed information as possible about all defects located at the time of the test. It is usually the responsibility of others to decide whether the inspected item can be accepted or not. The methods of NDT range from the simple to the complicated. Visual inspection is the simplest of all. Surface imperfections invisible to the eye may be revealed by penetrant or magnetic methods. If really serious surface defects are found, there is often little point in proceeding to more complicated examinations of the interior by ultrasonics or radiography.

Frequently it may be necessary to use one method of NDT to confirm the findings of another. Therefore, the various methods must be considered complementary and not competitive, or as optional alternatives. Each method has its particular merits and limitations and these must be taken into account when any testing program is planned.

Table 1 gives a sumary of the most frequently used NDT methods.

Table 1. Guide to NDT techniques

Technique cost	Access requirements	Equipment capital cost	Inspection cost	Remarks
Optical methods	Can be used to view the interior of complex equipment. One point of access may be enough.	B/D	D	Very versatile, little skill required, repays consideration at design stage.
Radiography	Must be able to reach both sides	A	B/C	Despite high cost, large areas can be inspected at one time; considerable skill required in interpretation
Ultrasonics	One or both sides (or ends)	B	B/C	Requires point-by-point search hence expensive on large structures; skilled personnel required.
Magnetic particle	Requires a clean and reasonably smooth surface	D	C/D	Only useful on magnetic materials such

Technique	Access requirements	Equipment capital cost	Inspection cost	Remarks
				as steel; little skill required; only detects surface breaking or near surface cracks
Penetrant flaw detection	Requires flaw to be accessible to the penetrant (that is, clean and at the surface)	D	C/D	For all materials some skill required; only detects surface-breaking defects; rather messy
Eddy current	Surface must (usually) be reasonably smooth and clean	B/C	C/D	For surface-breaking or near--surface flaws, variations in thickness of coatings, or comparison of materials; for other than simple comparison considerable skill is usually necessary (the exception is Amlec for surface-breaking cracks in steels)
Stress wave (acoustic emission)	Can be remote	A/D	A/B	Very versatile; will figure largely in the future; requires part to be loaded
Thermal	Either direct or remote	A/D	B/D	Varies from slow, simple and cheap to real-time, sensitive and costly
Holographic interferometry	Remote viewing possible	A/B	A/B	Specialized

x - This is only a rough guide where: A > \$ 500; B = \$ 100-500; C = \$ 10-100; D < \$ 10.

3. DESTRUCTIVE VS. NON-DESTRUCTIVE TESTING

The corresponding advantages and disadvantages of destructive and non-destructive tests are compared in table 2.

Table 2. Comparison of destructive and non-destructive tests

DESTRUCTIVE TESTS

Advantages:

1. Tests usually simulate one or more service conditions. Consequently, they tend to messure serviceability directly and reliably.

2. Tests are usually quantitative measurements of load for failure, significant distortion or damage, or life to failure under given loading and environmental conditions. Consequently they may yield numerical data useful for design purposes or for establishing standards or specifications.

3. The correlation between most destructive test measurements and the material properties being measured (particularly under simulated service loading) is usually direct. Hence most observers may agree upon the results of the test and their significance with respect to the serviceability of the material or part.

Limitations:

1. Tests are not made on the objects actually used in service. Consequently the correlation

NON-DESTRUCTIVE TESTS

Limitations:

1. Tests usually involve indirect measurements of properties of no direct significance in service. The correlation between these measurements and serviceability must be proved by other means.

2. Tests are usually qualitative and rarely quantitative. They do not usually measure load for failure or life to failure, even indirectly. They may, however, reveal damage or expose the mechanisms of failure.

3. Skilled judgment and test or service experience are usually required to interpret test indications. Where the essential correlation has not been proven, or where experience is limited, observers may disagree in evaluating the significance of test indications.

Advantages:

1. Tests are made directly upon the objects to be used in service. Consequently there is no doubt that the tests were made on representative test objects.

2. Tests can be made on every unit to be used in service,

or similarity between the objects tested and those used in service must be proven by other means.

2. Tests can be made on only a fraction of the production lot to be used in service. They may have little value when the properties vary unpredictably from unit to unit.

3. Tests often cannot be made on complete production parts. The tests are often limited to test bars cut from production parts or from special material specimens processed to simulate the properties of the parts to be used in service.

4. A single destructive test may measure only one or a few of the properties that may be critical under service conditions.

5. Destructive tests are not usually convenient to apply to parts in service. Generally, service must be interrupted and the part permanently removed from service.

6. Cumulative change over a period of time cannot readily be measured on a single unit. If several units from the same lot or service are tested in succession over a period of time, it must be proven that the units were initially similar. If the units are used in service and removed after various periods of time, it must be proven that each was subject to similar conditions of service, before valid data can be obtained.

if economically justified. Consequently they may be used even when great differences from unit to unit occur in production lots.

3. Tests may be made on the entire production part or in all critical regions of it. Consequently the evaluation applies to the part as a whole. Many critical sections of the part may be examined simultaneously or sequentially as convenient and expedient.

4. Many non-destructive tests, each sensitive to different properties or regions of the material or part, may be applied simultaneously or in sequence. In this way it is feasible to measure as many different properties correlated with service performance as desired.

5. Non-destructive tests may often be applied to parts in service assemblies without interruption of service beyond normal maintenance or idle periods. They involve no loss of serviceable parts.

6. Non-destructive tests permit repeated checks of a given unit over a period of time. In this way, the rate of service damage, if detectable, and its correlation with service failure may be established clearly.

7. Acceptable parts of very high material or fabrication costs are not lost in non-destructive testing. Repeated testing during production or service is feasible when economically and practically justified.

7. With parts of very high material or fabrication costs, the costs of replacing the parts destroyed may be prohibitive. It may not be feasible to make an adequate number and variety of destructive tests.

8. Many destructive tests require extensive machining or other preparation of the test specimens. Often, massive precision-testing machines are required. In consequence the cost of destructive testing may be very high, and the number of samples that can be prepared and tested may be severely limited. In addition such preparation and tests may make severe demands upon the time of highly skilled workers.

9. The time and man-hour requirements of many destructive tests are very high. Excessive production costs may be incurred if adequate and extensive destructive tests are used as the primary method of production quality control.

8. Little or no specimen preparation is required for many forms of non-destructive tests. Several forms of non-de structive testing equipment are portable. Many are capable of rapid testing or sorting and in some cases may be made fully automatic. The cost of non-destructive tests is less, in most cases, both per object tested and for overall testing, than the cost of adequate destructive tests.

9. Most non-destructive test methods are rapid and require far fewer man-hours or actual hours than do typical destructive tests. Consequently they testing all the production units at a cost normally less than, or comparable, to, the costs of inspecting destructively only a minor percentage of the units in production lots.

4. WHICH NDT METHOD TO CHOOSE?

The charts given on figs. 1 and 2 can be used in selecting a proper NDT method to detect defects in magnetic (or heavy) and non-magnetic (or light) metal. These charts are indicative but

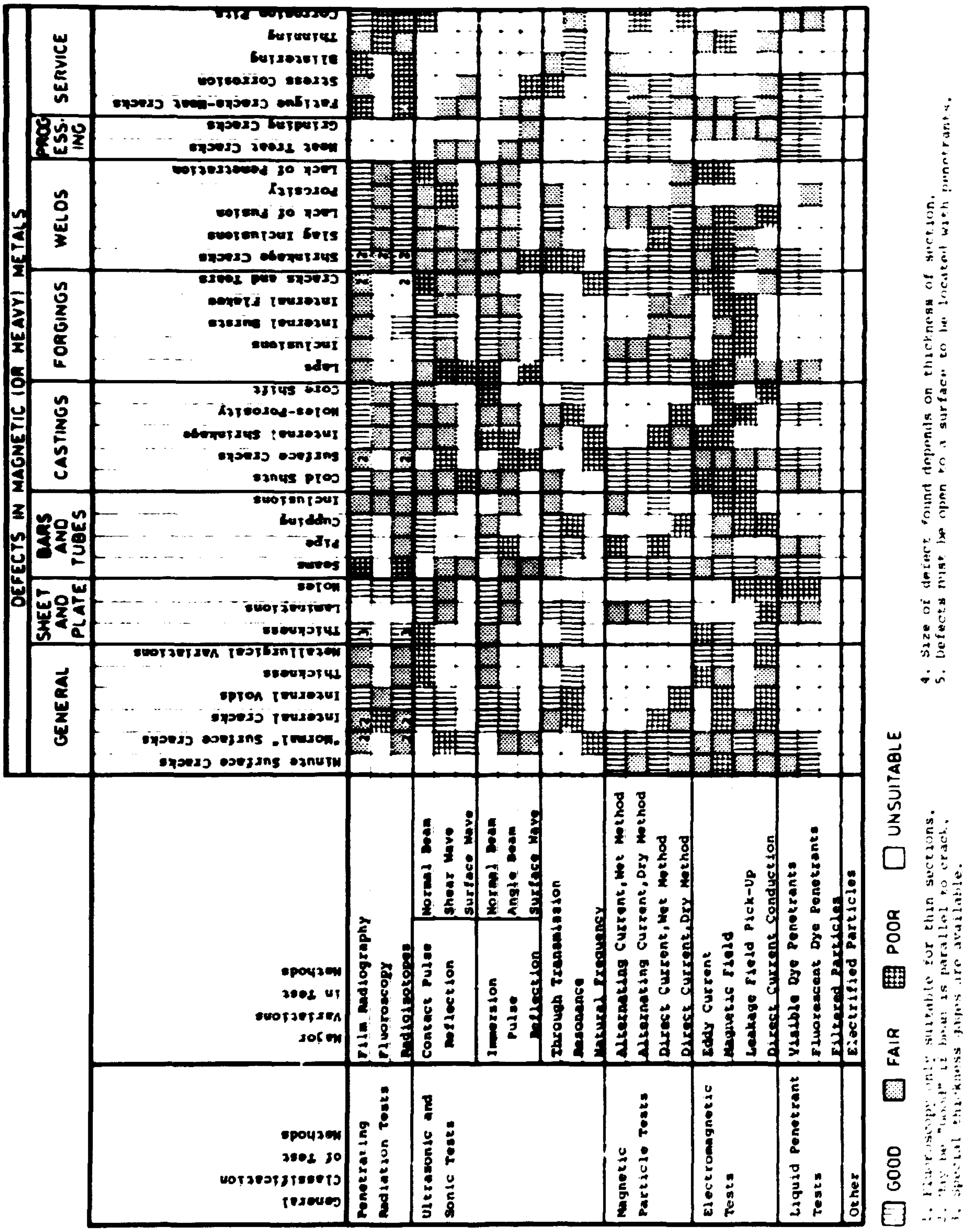
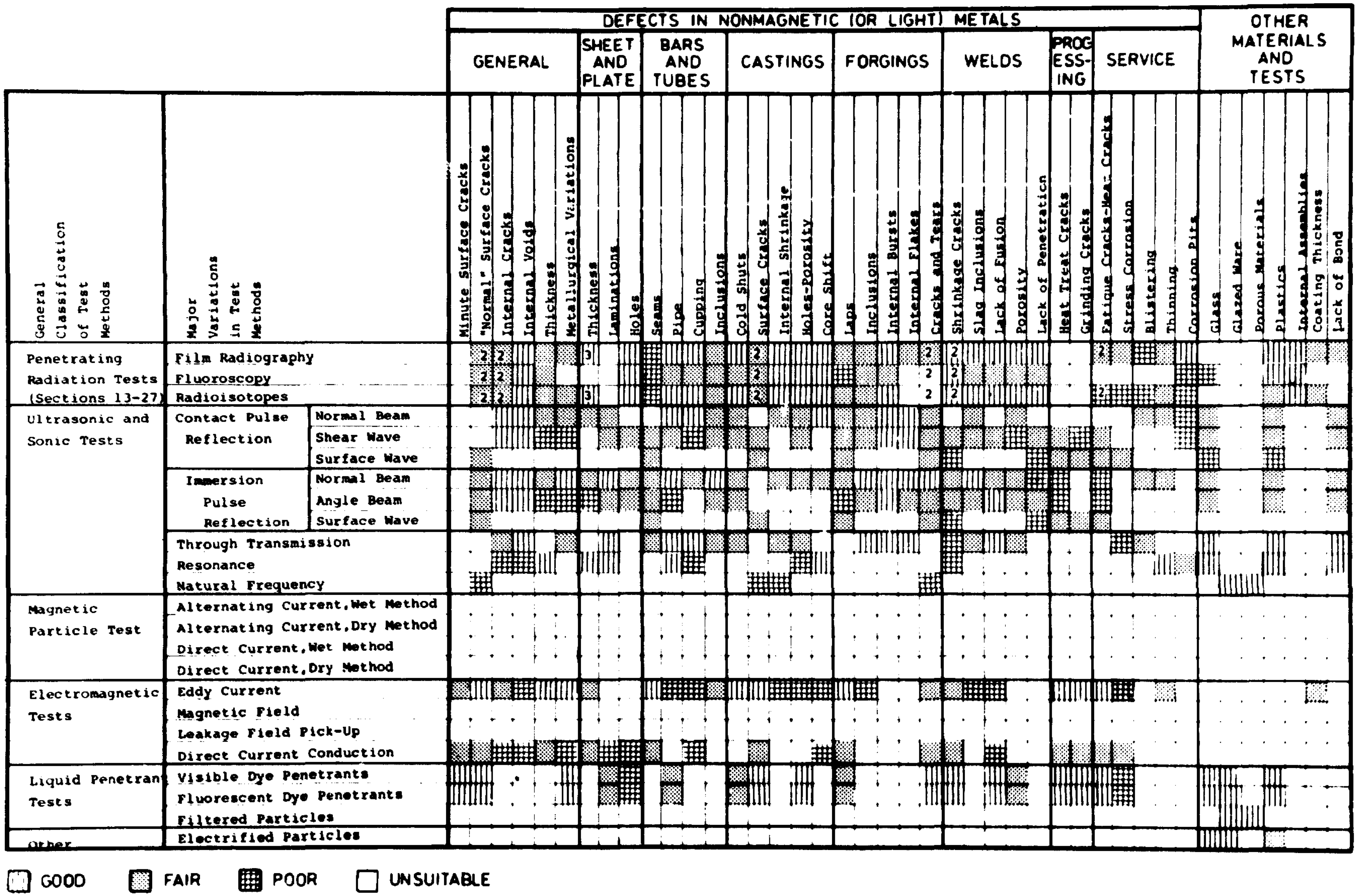


Fig. 1. NDT methods suitable for magnetic (or heavy) metals



1. Fluoroscopy of "light" metals much better than of "heavy" metals (Fig. 6).
2. Provided beam is parallel to the cracks.
3. Special thickness gages are available.
4. Size of defect found depends on thickness of section.
5. Defects must be open to a surface to be located with penetrants.

Fig. 2. NDT methods suitable for nonmagnetic (or light) metals

not conclusive. They are intended as a guide to the general abilities of each method and technique.

Although several other NDT techniques were mentioned in table 1, figs. 1 and 2 mentioned the 5 most important: radiologic, ultrasonic, magnetic particle, electromagnetic and penetrant tests.

The purpose of this paper is to describe only the application of radioisotopes to radiologic testing. However, to be able to better understand radioisotopic NDT techniques it is worth showing how the other techniques can detec defects, because, as mentioned before, the various NDT techniques complement rather than compete with each other.

5. NDT METHODS OTHER THAN RADIOLOGIC

Here only the principles of the 4 most widely used other--than-radiologic NDT methods will be explained.

5.1. Ultrasonic testing

Ultrasonic waves are mechanical vibrations which have a pitch beyond the range of audibility of the human ear. Their frequencies extend from about 20 kHz upwards, but the most useful range for the testing of metals is from 1 MHz to 10 MHz.

Ultrasonic waves are generated and detected by piezo-electric materials. A piezo-electric crystal is used to transmit pulses of energy into the material under examination. These travel through the material as stress waves, which are reflected back by the far boundaries of the material or by defects within it. The reflected pulses are received either by the transmitting crystal during a period when it is not in operation (fig. 3 - single probe, or pulse echo, technique) or by a separate receiving crystal (fig. 4 - double probe technique) and the stress pulses are converted back into electric signals that are displayed upon a cathode ray tube.

Fig. 3. Ultrasonic testing - single probe technique

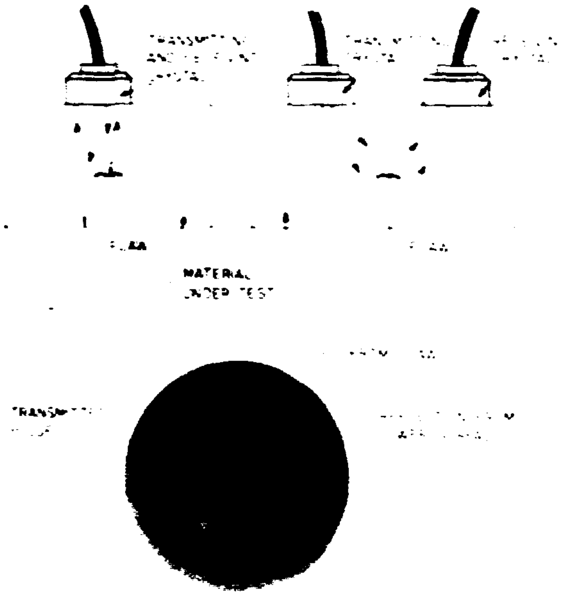


Fig. 4. Ultrasonic testing - double probe technique

5.2. Magnetic methods

Magnetic methods are suitable for the detection of surface defects in any material that can be magnetised. They can also be used, within limitations, to detect internal defects.

The magnetic particle technique is by far the most important technique of the magnetic methods. It is easy and quick in application, calls for simple apparatus, and provides results that are easy to interpret.

If a ferromagnetic (steel) component containing a crack of or very near the surface is magnetised, the lines of magnetic force will be confined within the material except where they cross the air-gap provided by the flaw. In this area they will be forced out of the material by their mutual repulsion as shown on fig. 5. If a fine dispersion of magnetic particles (usually fine iron-oxide powder) in thin transparent liquid is then applied to the surface, the magnetic particles will be attracted to the line of the crack and will thus indicate its presence as a black line.

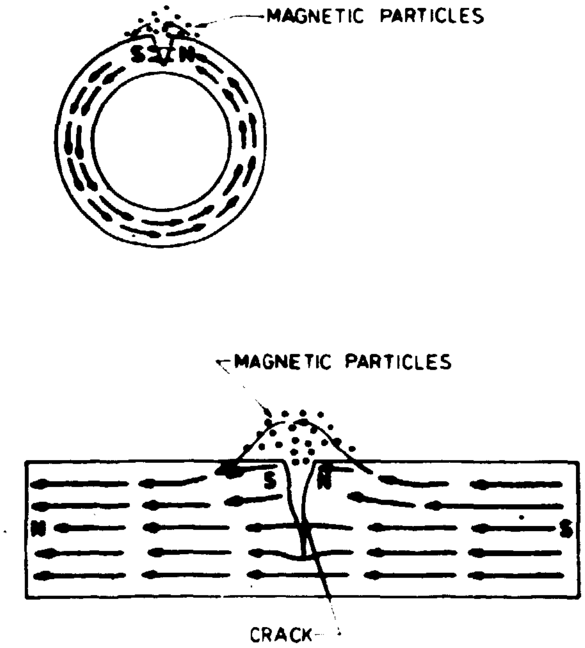


Fig. 5. Principle of magnetic flaw detection

5.3. Penetrant inspection

This method of testing depends upon the fact that surface defects or discontinuities can be penetrated by a liquid dye provided that the test piece is clean and free from foreign matter. After a period of time the excess penetrant is removed from the surface. The presence of the defect is then indicated by the dye left therein seeping out on to the surface by capillary action. In many cases this is aided by the use of a developer.

These three stages of the penetrant inspection process are shown on fig. 6 (a penetrant enters the crack; b excess of penetrant removed from surface; c developer seeps out penetrant and is dyed by it).

5.4. Eddy current testing

Eddy current testing is widely used for the detection of surface flaws in metallic objects and also for material sorting where metallurgical changes affect the electric or magnetic

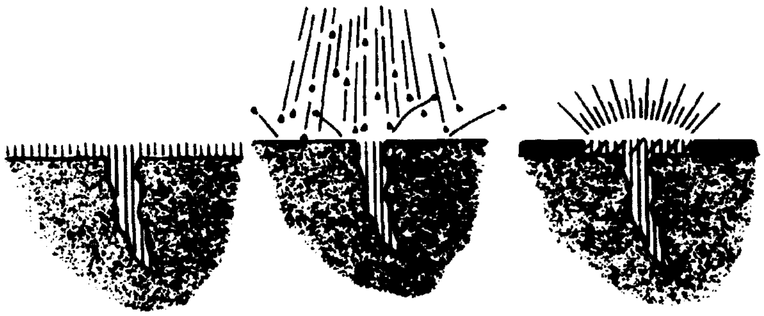


Fig. 6. Three stages of penetrant inspection
a - penetrant enters the crack; b - excess of penetrant removed from surface; c - developer seeps out penetrant and is dyed by it

properties of the test object.

If a coil carrying an alternating current is brought close to a conducting (metal) surface, the alternating magnetic field from the coil induces eddy currents in the surface of the metal. These eddy currents produce magnetic fields which are used either to change the inductance of the generating coil, and hence the current flowing through its windings, or to generate a voltage in a separate search coil. Compositional changes, defects in or very near the surface, and so on, modify the interaction between the coil and the conductor, and this effect can be detected by suitable equipment.

Figures 7-9 show three typical arrangements for eddy current testing with two coils (coil No. 1: generating coil, coil No.2: search coil).

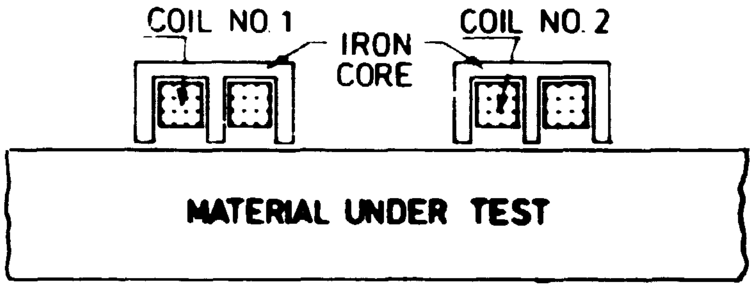


Fig. 7. Eddy current testing of a flat object

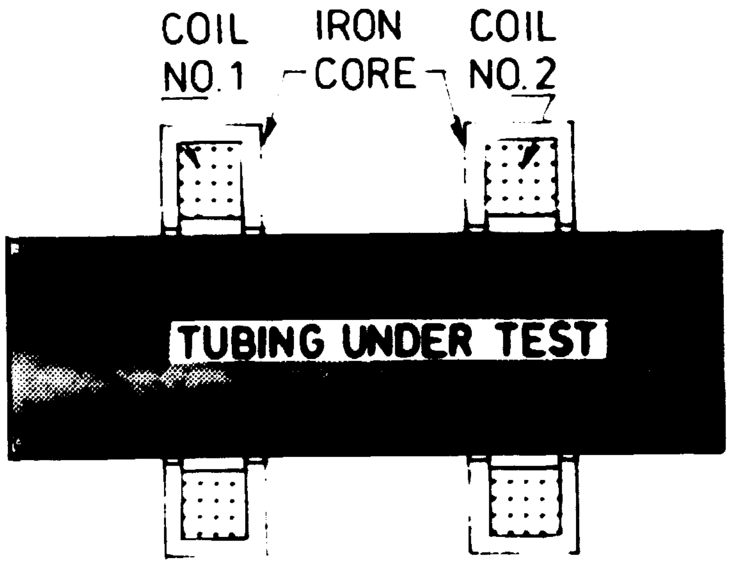


Fig. 8. Eddy current testing of a tube from the outside

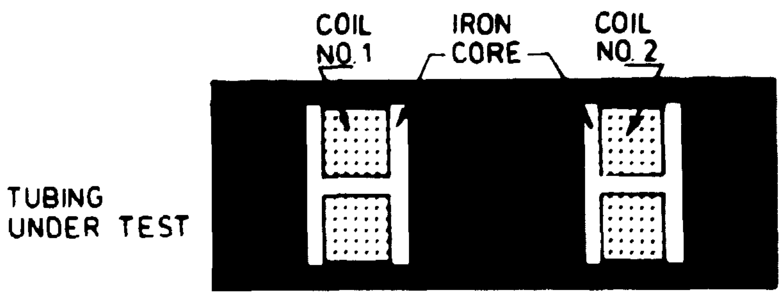


Fig. 9. Eddy current testing of a tube from the inside

6. RADIOLOGIC NDT METHODS

Radiologic NDT methods use penetrating electromagnetic radiation such as X-rays (produced by X-ray machines) or gamma-rays (produced by radioisotopes). This radiation, when passing through material, will suffer attenuation and a record of its intensity on the other side of the material will therefore provide a radiologic picture of the structure and composition of the material through which it has passed.

The radiologic picture mentioned above is not directly visible and it must be revealed by suitable detectors. There are three basic methods of doing this: by using a radiographic film (radiography) on which the radiologic picture is revealed as a shadowgraph, by using a fluorescent screen (fluoroscopy) on which a visible picture is produced, or by using a radiation detector (radiometry) which shows the difference in the radiation intensity emerging from the object under test.

X-rays are used in all three cases mentioned above whereas gamma-rays from radioisotopes are used in radiography and radiometry.

This presentation will deal mainly with the application of radioisotopes to radiography, because the application of radioisotopes to radiometry will be dealt with in the presentation of nuclear gauges.

6.1. The nature of X-rays and gamma-rays

X-rays are produced when electrons travelling at high speed collide with matter in any form. Gamma-rays are emitted spontaneously from the disintegrating nuclei of radioactive atoms. X-rays and gamma-rays are both forms of electromagnetic radiation like visible light, but with a very much shorter wave length (see fig. 10).

X-rays are emitted as a continuous band of wavelengths (a continuous spectrum), whereas gamma-rays are emitted as a number of discrete wavelengths (a line spectrum). The spectra of both kinds of radiation are shown on fig. 11.

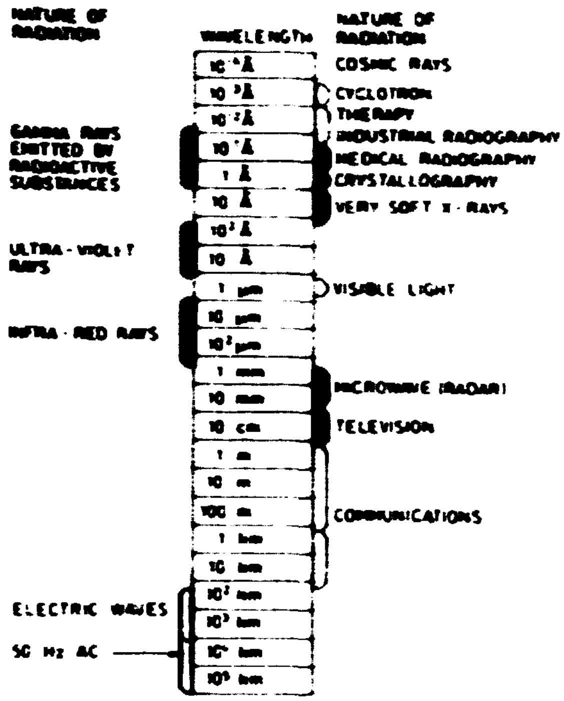


Fig. 10. Electromagnetic spectrum of radiation

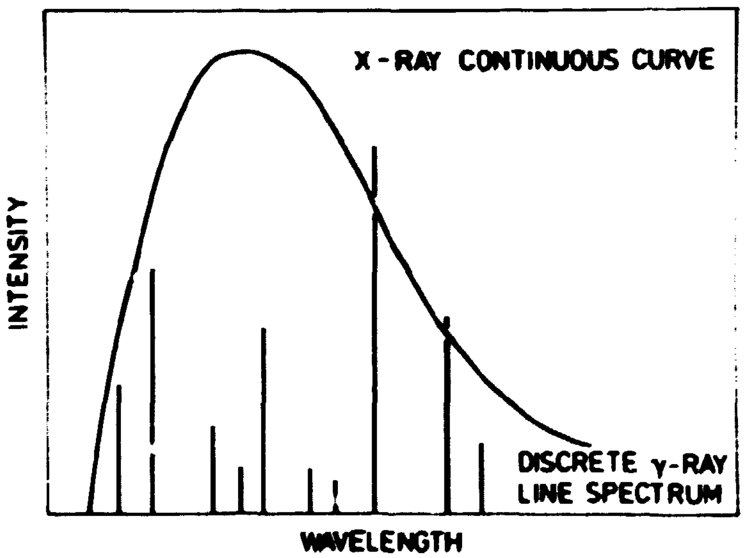


Fig. 11. Continuous spectrum of X-rays and line spectrum of gamma-rays

6.2. Quality and quantity of X-ray and gamma-rays

As shown on fig. 10, X-rays and gamma-rays are produced as electromagnetic radiation with different wavelengths. In practice the quality (penetrating power) of X-rays is given by the high voltage (in kilovolts kV) at which they were generated in an X-ray tube. Knowing this kilovoltage, one can calculate the minumum wavelength of the X-ray spectrum (see fig. 11) as follows:

$$\gamma_{min} = \frac{12.4}{U_{kV}} \qquad (1)$$

where γ_{min} is in Angstroms (1 Å = 10^{-8}cm) and U is in kV (1 kV = 1000 V). As can be seen, by increasing the kilovoltage applied to the X-ray tube one decreases the wavelength of the X-ray radiation (which means that the X-rays have more penetrating power).

As can be seen from fig. 12, the increase of kilovoltage not only changes the quality of the X-rays but also increases their intensity (quality).

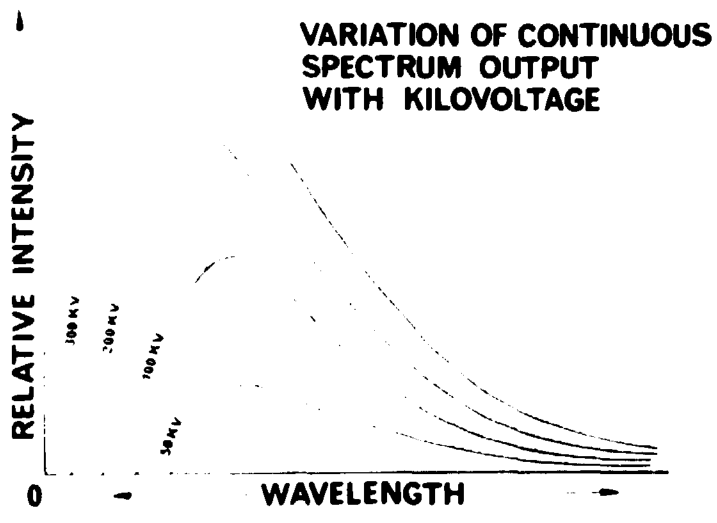


Fig. 12. Changing the kilovoltage changes both the quality as well as the quantity of X-rays

One can however, indrease the intensity (quantity) of X-rays without changing their quality (see fig. 13) by increasing the current flowing through the X-ray tube (milliamperage).

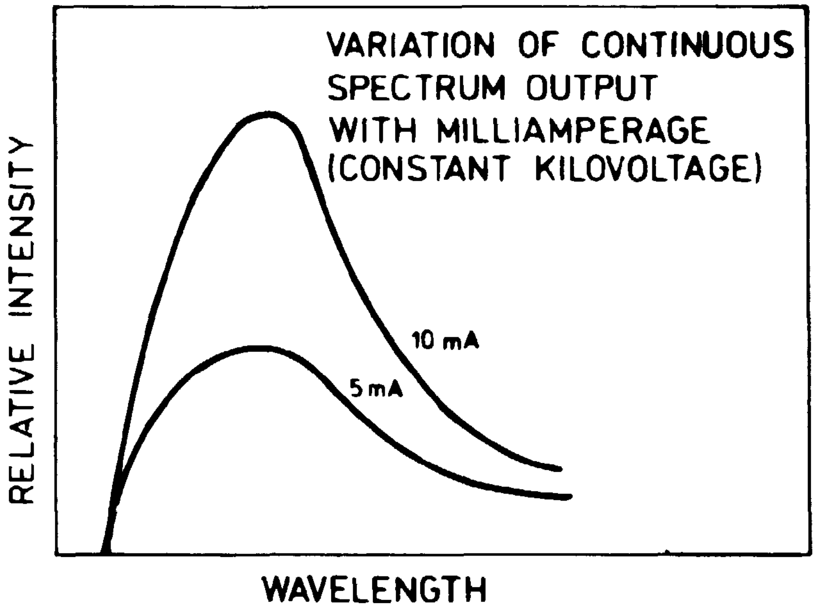


Fig. 13. Changing the milliamperage changes only the quality of X-rays

In almost every X-ray machine both the kV as well as the mA setting can be changed by adequate controls.

Such a control of the quality and quantity of gamma-radiation emerging from a particular radioisotope is impossible. Each radioisotope has its own spectrum of gamma-radiation, which is characteristic for that particular radioisotope and cannot be changed.

The quality of gamma radiation emitted by a radioisotope is given in MeV (megaelectronovolts; 1 MeV = 1000 keV = 1000 000 eV). Each spectral line of a particular radioisotope (as shown on fig. 11) has its specific energy (expressed in MeV). E.g., the Caesium-137 (^{137}Cs) radioisotope has only one spectral line of gamma-rays of 0.66 MeV energy. Cobalt-60 (^{60}Co) has two lines: 1.17 and 1.33 MeV and Iridium-192 (^{192}Ir) has many lines with energies ranging from 0.29 to 0.61 MeV (^{60}Co, ^{192}Ir and ^{137}Cs are radioisotopes mostly used for industrial radiography).

It is worth remembering that it is not possible to change the energy of the gamma-radiation of a particular radioisotope just as it is not possible to chose only one (or more) of the spectral lines from its entire spectrum (all lines are always present).

This is the first basic difference between X-rays (produced in an X-ray machine) and gamma-rays (produced by a radioisotope): the energy of X-rays can be changed, the energy of gamma-rays is constant.

As shown on fig. 13, the quantity of X-rays from an X-ray machine can be changed by changing the milliamperage of the machine. Such a quantity control is impossible for a radioisotopic gamma-ray source. The quantity of gamma-radiation coming from such a source depends on the activity of the source (on the amount of radioactive atoms present in the source). The activity of a radioisotopic source is measured in Curies (or millicuries; 1 Ci = 1000 m Ci).

A source has an activity of 1 Ci if the number of radioactive disintegrations per second equals 3.7×10^{10}.

In practice, radiation quantity is measured in roentgens (R) and radiation intensity in roentgens per hour (R/h). Another characteristic property of a particular radioisotope is the specific gamma-radiation output per Curie (also called the gamma-constand, k_γ, and measured in roentgens per hour per Curie at 1 m distance from the source, $R/Ci.h.m^2$).

As can be seen, the only way to increase the quantity of gamma-rays emitted by a radioisotope source is to increase its activity. As radioisotopic sources are produced with a given activity, it is not possible to change this activity for a particular source.

This is the second basic difference between radioisotopes and X-ray machines: the radiation output of an X-ray machine can be changed but it is well determined for a particular radioisotope.

The radiation output of a radioisotopic source changes however with time as the radioisotope disintegrates (decays). The third characteristic property of a radioisotope is its half-life ($T_{½}$), i.e. the period of time after which the activity of the radioisotope falls to 50% of its initial value.

These three characteristic values of a particular radio-isotopic source (gamma-ray energy, specific gamma-ray output and half-life) must be taken into account when choosing a radioisotope for radiography or radiometry.

Although there are several hundred radioisotopes, only a few are widely used for radiography. It would be very desirable to have a large choice of sources with gamma-ray spectre covering the energy range from at least 0.1 to 10 MeV, so as to have sources suitable for all specimen thicknesses, but radioisotopes with suitable half-lives and specific activities are not available.Practically all industrial radiography is done with the five radioisotopes listed in table 3.

Table 3. Radioisotopes most frequently used for radiography

Radioisotope	Main gamma-ray lines MeV	Specific gamma-ray output $R/Ci.h.m^2$	Half-life
Cobalt ^{60}Co	1.17,1.33	1.35	5.3 years
Caesium ^{137}Cs	0.66	0.33	30 years
Iridium ^{192}Ir	0.30-0.61	0.48	74 days
Thulium ^{170}Tm	0.052,0.084	0.0025	127 days
Ytterbium ^{169}Yb	0.063-0.31	0.125	31 days

Many other radioisotopes have been used to a limited extent, but most have certain disadvantages.

6.3. Principles of defect detection

The formation of the radiologic image of an object under NDT radiologic examination is based on the effect of the attenuation of the radiation during its passage through matter. This is governed by the attenuation law:

$$J = J_o e^{-ux}, \tag{2}$$

which is graphically presented on fig. 14.

If an X- or a gamma-radiation beam of intensity J_o passes through a speciment of thickness _t_, in which a defect of thickness _d_ is present, then the radiation of intensity J_o will be attenuated to different degree under the "sound" part of the object (of thickness _t_,

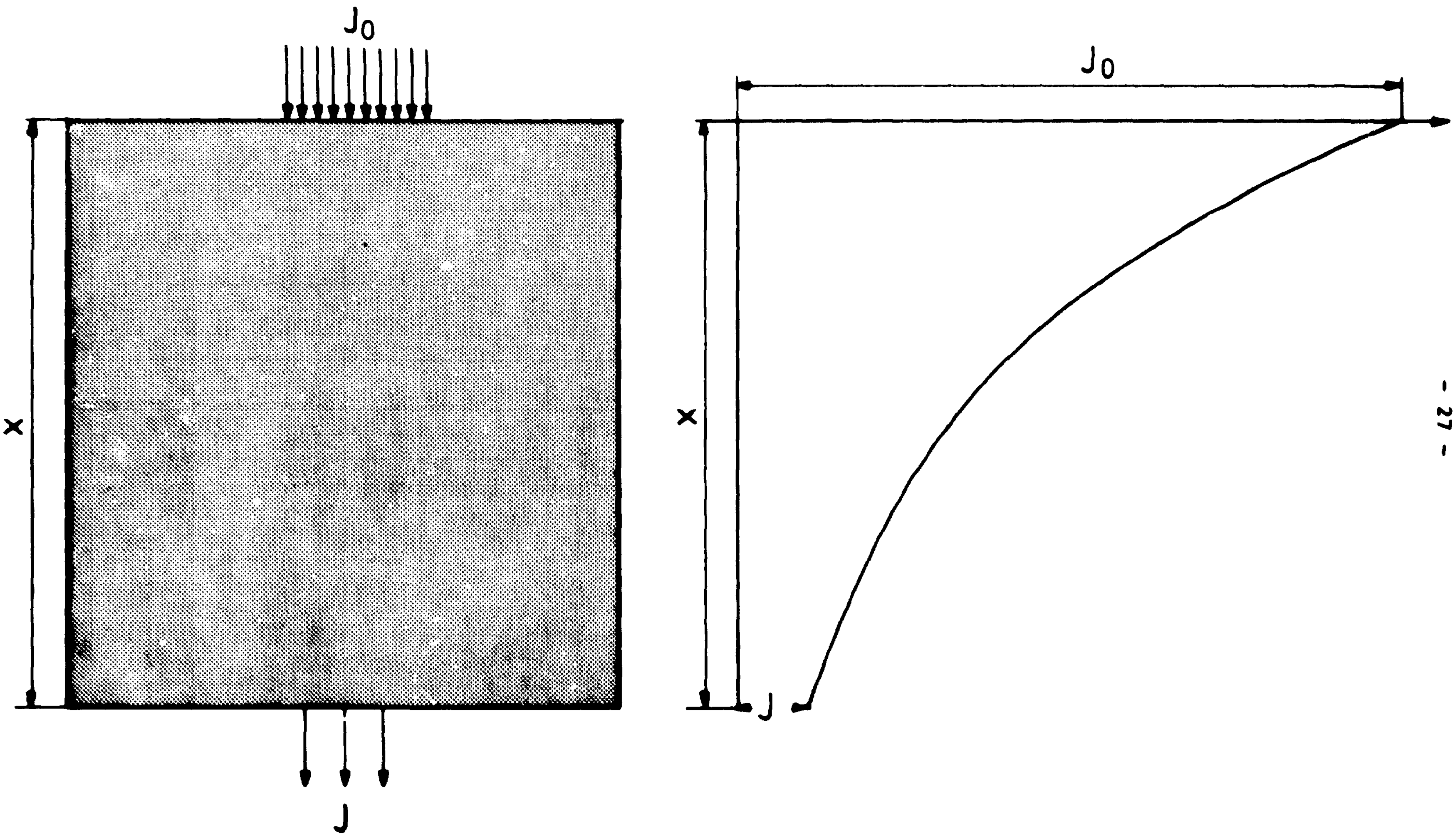


Fig. 14. Attenuation of radiation by matter

$$J = J_o e^{-\mu t}, \tag{3}$$

and under the part where the defect is present (thickness of material without defect t-d)

$$J_d = J_o e^{-\mu(t-d)}. \tag{4}$$

Equation (4) is valid in the case when the defect of thickness <u>d</u> is a void and therefore does not attenuate the radiation at all. If, however, an inclusion is present in the object as a defect, then the radiation intensity under the defect will be:

$$J_o = J_o{}^{-\mu(t-d)-\mu_d d} \tag{5}$$

where μ is the attenuation coefficient of the "sound" material, and μ_d is the attenuation coefficient of the included material.

In both cases

$$J_d \neq J \tag{6}$$

there is a difference of radiation intensity in the radiation beam emerging from the object under examination, as shown on fig. 15.

Those two cases of defect detection (a void with attenuation coefficient $\mu_d = 0 < \mu$ or an inclusion with $\mu_d > \mu$) are graphically presented on fig. 16.

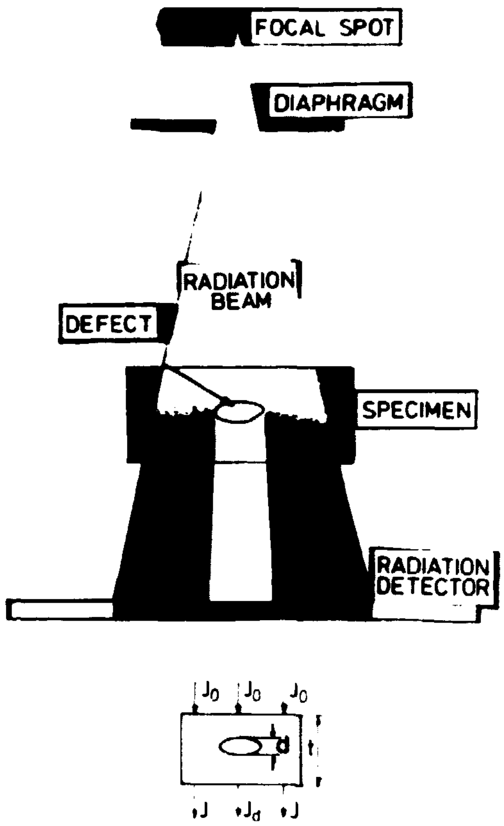


Fig. 15. Principle of radiologic image formation

This simplified example of radiologic image formation can be extended to a general statement:

> radiation which has passed defective spots in the form of (empty) voids has more intensity that radiation which has passed through inclusions (of higher material density).

The whole technique of radiologic NDT consists of finding an efficient mode of detecting and visualizing these radiation intensity differences. Before such methods will be described, attention must be drawn to the obvious fact that if the presence of a defect in the object under examination causes a greater difference in radiation intensity it will be easier to detect it. Therefore first efforts in radiologic NDT must be concentrated on obtaining the highest possible contrast in the radiologic image.

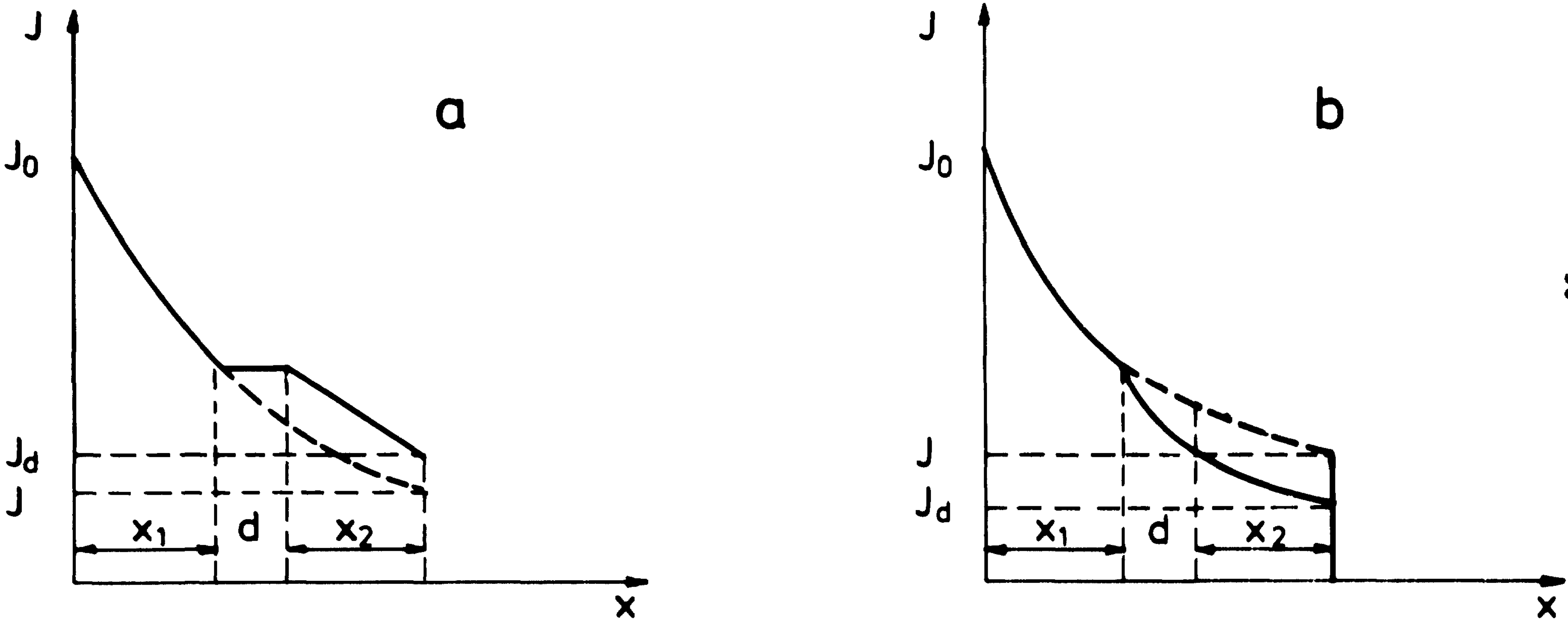


Fig. 16. Attenuation of radiation under a defect

As shown above, the intensity of radiation which has passed through the material depends on its attenuation coefficient μ. This in turn depends both on the properties of the material itself (materials of higher density, with higher atomic number, have higher attenuation coefficients) and on the radiation energy. Two two basic principles must be remembered:

1) Radiation of a constant energy is more attenuated by heavy materials than by light ones.
2) The same material will attenuate radiation of a high energy less than radiation of a lower energy.

The second statement is well illustrated on fig. 17 for radiations of different energies: $\mu_1 > \mu_2 > \mu_3$, because $E_1 < E_2 < E_3$.

It is obvious that by using radiation of lower energy one can obtain better contrast of the radiologic image.

6.4. How can a radiologic image be seen?

As mentioned before, there are three main methods to visualize the radiologic image. The first and most widely used method is radiography. By using X-ray film or paper as detector of the radiologic image, one can produce a shadowgraph of the object under examination. Regions of lower X-ray or gamma-ray attenuation will be shown as black areas, whereas white areas will be produced in areas where attenuation was higher.

If a fluorescent screen is used instead of the X-film, a visible picture will be produced on it. However, here areas of higher radiation intensity will give a brighter image than those of lower intensity. Fluoroscopy, very often used with X-rays, is not suitable for gamma-rays because of their high energies or low intensities.

The third method of visualizing a radiologic picture is the measurement of radiation intensities by radiation detectors such as e.g. scintillation counters. This is done in radiometry. Here radioisotopes are very often used. The intensities of the gamma-rays passing through the object under examination are either registered on a chart recorder or shown in the form of a scintigraph.

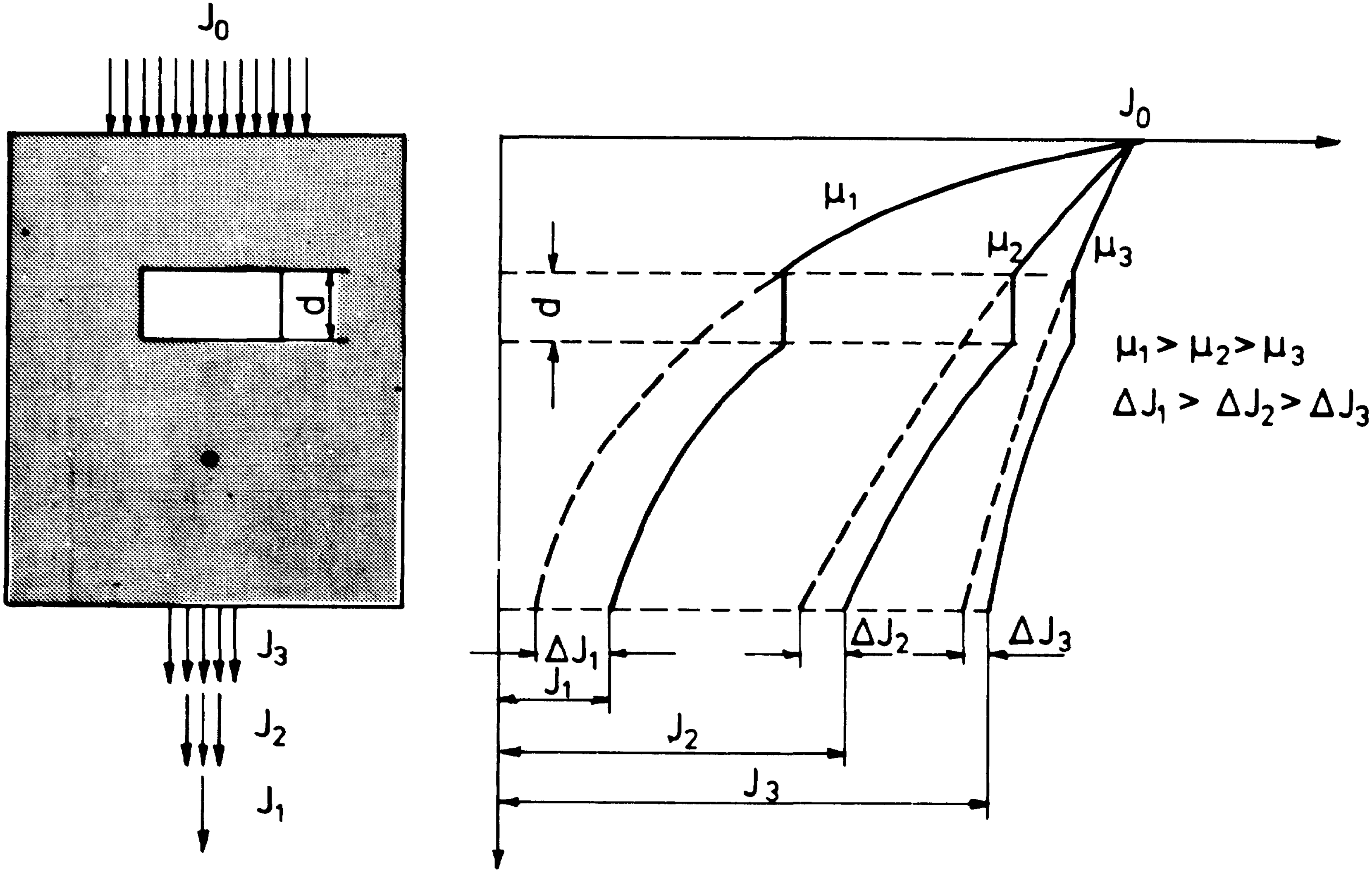


Fig. 17. Influence of radiation quality on radiologic contrast

7. PRINCIPLES OF RADIOGRAPHY

Radiography is so far the most widely used method of NDT. As is well known, X-rays and gamma-rays produce blackening of the X-ray film. The optical film density is the measure of this blackening. The X-ray film in which the radiologic picture was produced (radiograph) is interpreted against a visible light source (on the so-called illuminators).

The density of an X-ray film is defined as:

$$D = \log \frac{L_o}{L} \tag{7}$$

where L_o is the light intensity falling onto the film and L is the intensity transmitted through the film.

The density produced on an X-ray film depends on the dose (quantity) of radiation reaching the film. This in turn is a product of radiation intensity and time of exposure, so:

$$P = J.\underline{t} \tag{8}$$

where P is the radiation dose (measured in roentgens, R).

J is the radiation intensity (e.g. in R/h)
t is the exposure time.

It is quite obvious that the longer an X-ray film is exposed to radiation, the blacker it will be. However, the relation between the film density and its exposure dose is not linear. The relation between the film density and exposure is called the characteristic curve of the X-ray film.

X-ray films available for radiography differ in their sensitivity to radiation (speed) and have different contrasts. Fig. 18 shows the characteristic curves of different brands of X-ray films from the same manufacturer. Here the film density is plotted against the logarithm of exposure. As can be seen, different exposures are necessary to reach the same density on different film brands. Thus, comparing exposures necessary to produce the same film density, relative speed can be computed.

For the films shown on fig. 18, if the relative speed for the M film is chosen as 1 (at e.g. density D = 2), then by comparing the relative log exposures for other films with that of the M film, their relative speed can be determined.

From fig. 18 one can read that, for D = 2 the relative log exposure for the M film is 3.22, whereas e.g. for the film C it is 2.7, for film D 2.35 and for Kodisex 2.07. Thus the difference of relative log exposure between films M and C is 0.52, between M and D 0.87, and between M and Kodirex 1.15. The corresponding differences in exposures will be: 3.31; 7.41 and 14.13, which means that the Kodirex film is 14.13 times faster than the M film, the D film is 7.41 times faster, and the C film is only 3.31 times faster.

The slope of the characteristic curve is the measure of the contrast of the film. As can be seen, this contrast increases with the film density.

It has already been demonstrated that it is essential to have high contrast of the radiologic image itself to be able to detect small differences in radiation intensity. Now, it will be shown that the choice of a proper exposure of an X-ray film is also essential in this respect.

As shown on fig. 15, radiation emerging from an object in which a defect is to be detected shows an intensity difference

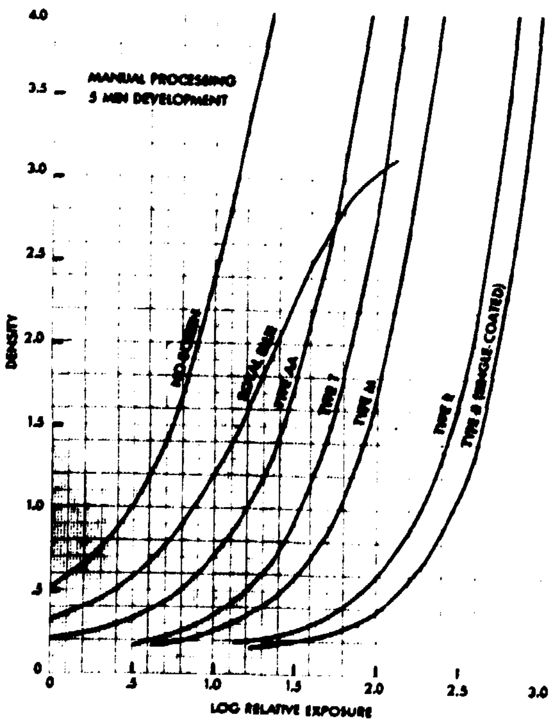


Fig. 18. Characteristic curves of X-ray films

$\Delta J = J - J_d$ between the "sound" area and the area containing the defect. For a given exposure time t this will give a dose difference of $\Delta P = \Delta J . t$ when reaching the film.

Fig. 19 shows that it is much better to expose the film to a higher density, because then the same dose difference ΔP will produce greater difference in the film density ΔD, and thus the defect will be better visible on the radiograph. So it is advisable to use the upper portion of the characteristic curve of the film, where film contrast is higher. For practical reasons, X-ray films are exposed so as to reach densities between D = 2 and D = 3. Films of higher densities, although showing better contrast, are difficult to interpret.

As shown by fig. 18, films of different speed are available fo radiography. It must be remembered, however, that films of higher speed show larger grain size (and vice versa) and a coarse grain film will not give the sharp radiographs that are necessary to reveal minute defects. thus, when choosing the appropriate film speed one must take into account the type of defects to be revealed.

In industrial radiography X-ray films are usually used with an intensifying screen to shorten exposure time. Lead foils are mainly used as intensifying screens but sometimes fluorocmetallic screens (combination of a lead and a fluorescent screen) are also used. Fluorescent screens, which give the highest intensification, are very seldom used in radioisotope radiography, because they give much less sharp radiographs than those taken with lead screens.

The problem of the sharpness of radiographs is of primary importance in radiographic defect detection. As mentioned above, a high speed, coarse grain film will give a rather unsharp radiograph. Also intensifying screens can contribute to image unsharpness. All this unsharpness is called inherent unsharpness. For X-rays of low energy this, unsharpness can be as little as 0.1mm, whereas for radioisotopes (such as ^{60}Co or ^{137}Cs) it can reach 0.3 mm.

Another important source of unsharpness is the geometric unsharpness caused by the finite dimensions of the radiation source (for a point source, the geometric unsharpness will disappear). This is best illustrated by fig. 20. It is obvious that one can reduce the geometric unsharpness u_g either by

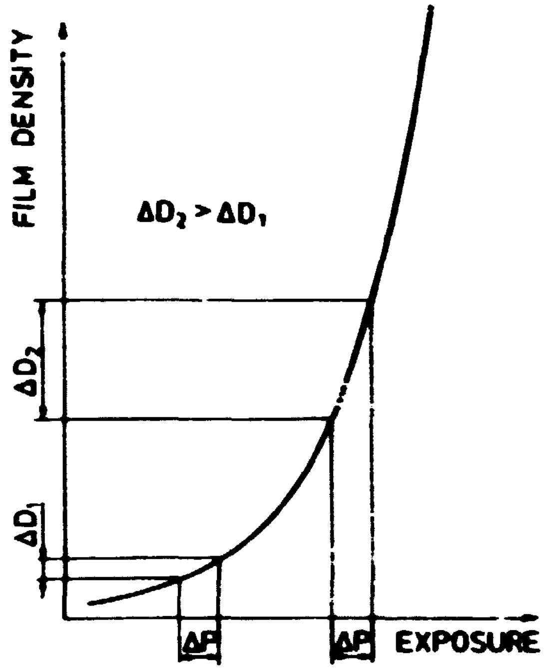


Fig. 19. Radiographic contrast

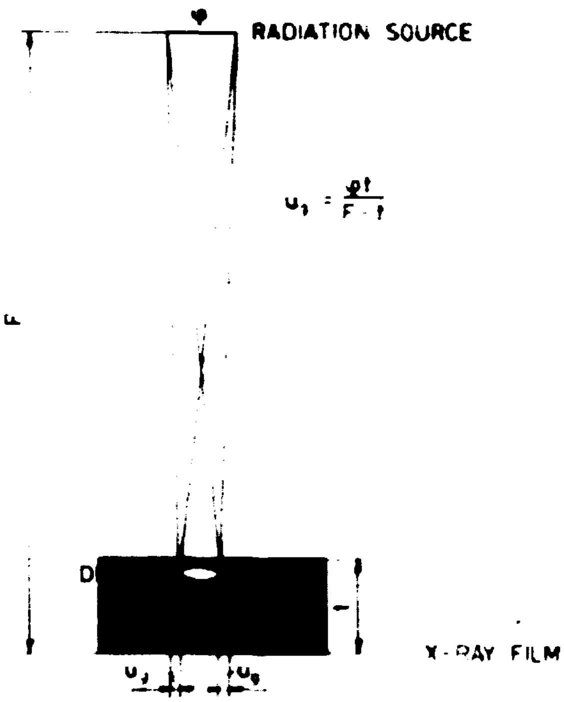


Fig. 20. Geometric unsharpness of a radiograph

reducing the size of the radiation source ϕ or by increasing the focus film distance F. Each X-ray tube has a certain size of focus (generally between 0.5 and 5.0 mm) which cannot be changed. Also each radioisotope source has a fixed size (generally between 0.5 and 4.0 mm). If one wishes to decrease the focus, then another X-ray tube or another radioisotopic source must be chosen. In both cases the reduction of the focus size can only be made at the cost of reducing the intensity of the radiation source. There are some limits in this respect.

One can decrease the geometric unsharpness by increasing the focus film distance (FFD)-F. This is also done at the cost of the radiation intensity reaching the film, because of the inverse square law of radiation intensity, which states that the radiation intensity decreases with the square of the FFD.

On the other hand, it is not necessary to decrease the geometric unsharpness below the inherent unsharpness of the X-ray film. Thus

$$u_g = u_i \tag{9}$$

Usually one has to choose the FD for a given thickness of material t and radiation source size ϕ. This can be done by transforming the formula for geometric unsharpness:

$$u_g = \frac{t.\phi}{F} \tag{10}$$

into:

$$F_{min}\ t\ \frac{\phi}{u_g} + 1. \tag{11}$$

Formula (11) gives the minimum FFD still acceptable to obtain a sharp radiograph.

8. RADIOGRAPHIC QUALITY

It has already beeb demonstrated that there are many factor that can contribute to the deterioration of the quality of a radiograph. It can have poor contrast because the energy of radiation was not correctly chosen, it can be unsharp because of too large a radiation source, too short an FFD or too large grain of the X-ray film. The quality of a radiograph can further deteriorate by faulty processing and film handling.

To be able to assess the final quality of a radiograph, Image Quality Indicators (IQI) are used. They are prescribed both by international as well as national standards. The main purpose of these indicators is to prove that the quality of a radiograph lies within the prescribed limits, that all the exposure, processing and handling factors have been chosen properly.

The IQIs in the form of wires of different diameters, or plates of different thickness with holes drilled in them, are placed beside the object under examination and are radiographed with it. The quality of the radiograph is deemed adequate if the smallest prescribed wire or hole is visible on the radiograph.

There are three main types of IQIs in general use. The ISO recommends the use of either a wire IQI (see fig. 21) or

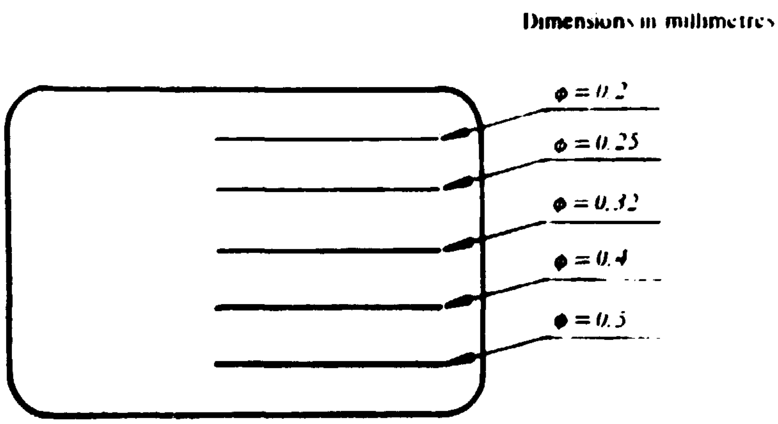


Fig. 21. Wire type ISO IQI

a step and hole IQI (see fig. 22). The wire IQI consists of a series of wires of different diameters with a ratio of $\sqrt[10]{10}$ whereas the step and hole IQI consists of an assembly of steps with one (or more) circular holes of a diameter equal to the thickness of the step. The ratio of step thickness (and hole diameters) is the same as for the wire IQI, i.e. $\sqrt[10]{10}$.

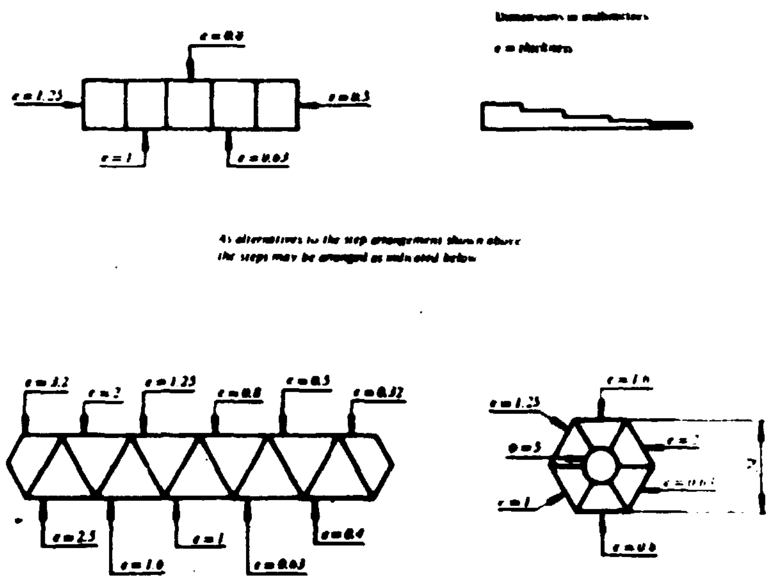


Fig. 22. Step-and-hole type ISO IQI

Different IQIs are used in the USA (they are still called penetrameters). The best known is the ASTM design (see fig. 23) which consists of a uniform thickness plate containing three drilled holes of diameters equal to T, 2T and 4T (where T is the thickness of the plate).

It is always required that the IQI be produced from the same material as the radiographed object.

To be of any use for the assessment of the quality of any radiographic technique, it is necessary to know what IQI sensitivities should be obtainable. Several standards quote the required IQI sensitivities (in per cent of the thickness of the radiographed material). This means, in practice, that on the radiograph a wire or hole on the IQI should be visible that has a lesser (or equal) per cent thickness (or diameter) than required by the standard.

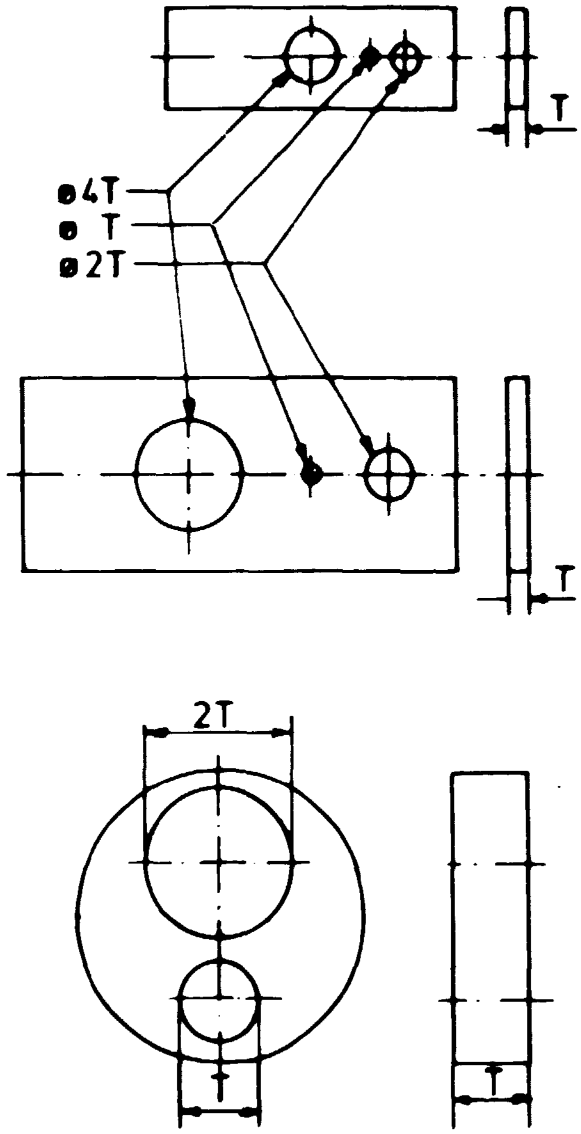


Fig. 23. ASTM type IQI

The ISO 2504 International Standard "Radiography of Welds and Viewing Conditions for Films - Utilization of Recommended Patterns of Image Quality Indicators (I.Q.I.)" gives the following acceptable image quality values on steel.

Table 4. Examination by gamma rays from Iridium 192

Dimensions in mm

Steel thickness		Visibility required	
above	under or equal to	of the hole with diameter	of wire with diameter
10	16	0.8	0.32
16	25	0.8	0.4
25	32	1.0	0.5
32	40	1.0	0.5
40	60	1.25	0.63
60	80	1.25	0.8
80	100	1.6	1.0

Table 5. Examination by gamma rays from Cobalt 60

Dimensions in mm

Steel thickness		Visibility required	
above	under or equal to	of the hole with diameter	of wire with diameter
25	32	1.25	0.8
32	40	1.25	1.0
40	50	1.6	1.0
50	80	1.6	1.25
80	100	2.0	1.25

In general a 2% IQI sensitivity is acceptable. Sometimes a 1% sensitivity is required.

Fig. 24 shows percent IQI sensitivity curves that can be obtained for steel at different thicknesses using wire type (curve A) or step-hole (curve B) IQIs.

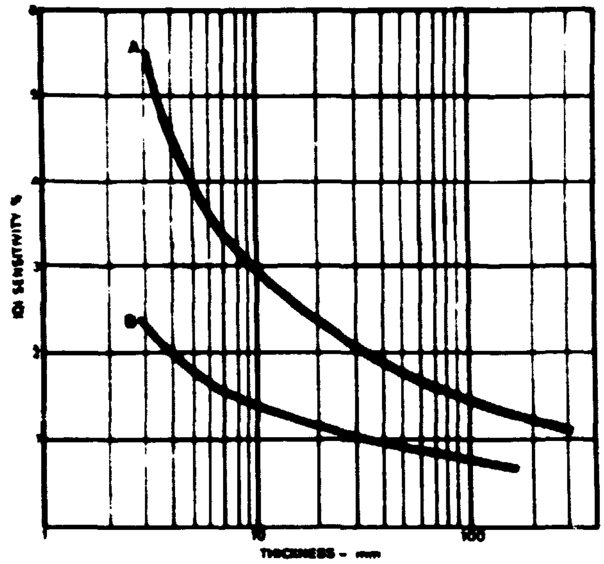


Fig. 24. Percent IQI sensitivity for steel. A-wire IQI B-step-hole IQI

9. RADIATION SOURCES

X-rays and gamma-rays, both being penetrating electromagnetic radiation, have the same properties and interact in the same way with matter. From the point of view of the radiologic NDT, there is no difference whether the radiation originates from an X-ray tube or from a radioisotope, if it is of adequate quality and of the quantity necessary for the particular purpose.

Table 6 gives a list of various X-ray sources and their application in radiography whereas table 7 gives a comparison between X-ray and gamma-ray sources used for radiography of steel specimens.

Table 6. X-ray equipment and its application in radiography

Maximum kilovoltage	Description	Output		Weight of head (kg)	Focal spot size (mm)	Maximum thickness which can be examined		Typical applications
		mA	$R/min \cdot m^2$			steel (cm)	light alloy (cm)	
50 kV	HT cable: Be window	30	10	6	1.5x1.5	-	0.5	Extremely thin
80 kV	lightweight tanks	2	-	9	1x1	0.3	3	metals; plastic; wood; packages
150 kV	portable, tank type	3	-	23	1x1	2.5	10	Thin steel welds; light alloy castings
250 kV	laboratory, tank type	10	-	500	4x4	6	17	Steel welds;
250 kV	portable, shipyard	8	-	70	3x3	5	16	small castings
300 kV	laboratory, HT cables	10	40	100	4x4	7.5	22	Most steel welding,
300 kV	portable, shipyard	5	16	60-110	3x3	7	20	e.g. pressure
400 kV	laboratory, HT cables	10	50	350	4x4	10	25	vessels
400 kV	resonance	10/3	-	750	4x4	10	25	
1000 kV	resonance	3	50	1000	7x7	12	50	Large steel castings
1000 kV	Van de Graaff	0.25	8	450	2x2	12	50	Ammunition (shells,
3000 kV	Van de Graaff	0.3	350	3600	2.5x2.5	30	-	fuses)
8 MV	linac (travelling wave)	-	1500	3300	3x3	40	-	
7.5 MV	linac (standing wave)	-	1500	550	2x2	40	-	Thick steel welds
18 MV	betatron	-	100	2000	0.3x0.3	30	-	Steel castings,
24 MV	betatron	-	150	2500	0.2x0.2	40	-	particularly stain-
24 MV	linac	-	25000	2500	2x2	50	-	less steels
31 MV	betatron	-	150	4500	0.2x0.2	40	-	Rocket motor propellant

Table 7. Radiography of steel specimens

X-rays (kV)	High sensitivity technique maximum thickness (mm)	Low sensitivity technique maximum thickness (mm)
100	10	25
150	15	50
200	25	75
250	38	88
400	75	110
1000	125	160
2000	200	250
8000	300	350
30000	325	450
Gamma-rays		
^{192}Ir	60	100
^{137}Cs	100	110
^{60}Co	125	185

It is not the purpose of this presentation to describe the X-ray equipment, although in most cases it can be used for the same purpose as the radioisotopes. Therefore only radioisotopic sources will be described here.

Table 3 listed the main radioisotopes used nowadays for NDT. For gamma-radiography, these radioisotopes are available in the form of sealed gamma-ray sources. According to the Draft International Standard ISO/DIS 3999 "Apparatus for gamma-radiography Specification" (1976), a gamma radiography sealed source is defined as follows: "A sealed source in a form suitable for use in radiography, which comprises the radioactive material, usually in the form of a pellet or pellets, sealed in one or more capsules". The source holder has the following definition: "A device by means of which the gamma radiography sealed source(s) can be fixed in the exposure container or at the head of a remote control device". They are produced according to international (ISO) and national standards in the form of sealed, cylindrical capsules, built together with a source holder (see fig. 25). The active part of the source usually has a cylindrical form, the diameter and height of which are given in the catalogue. Most gamma-ray sources used for radiography have a "square" form, i.e. the diameter of the active part is equal to its height.

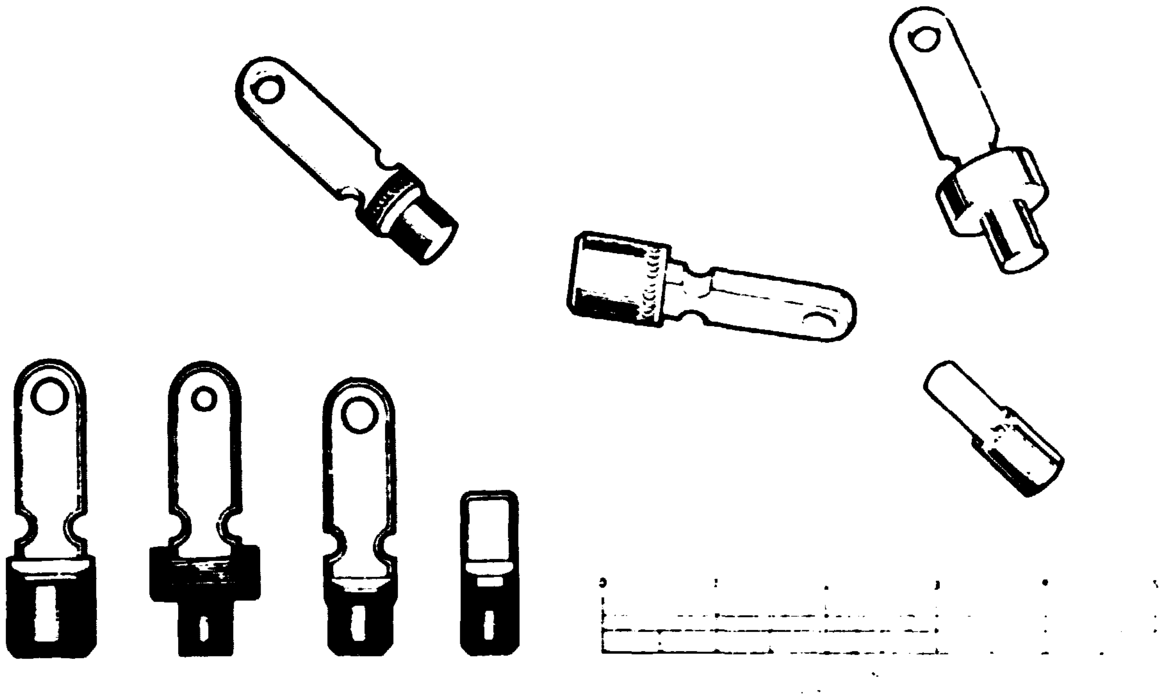


Fig. 25. Radiographic gamma ray sources

In table 8 dimensions of the active part and maximum equivalent activities (in Ci) are given together with the gamma-ray constant (quoted already in table 3) (in R/Ci.h.m^2). Knowing the source activity and its K_γ, the source output at 1 m can be calculated (such outputs for the maximum activity of each source are also given in table 8.

Table 8. Gamma radiography sources

Radioisotope	K_γ R/Ci.h.m^2	Dimensions of active part dia.×length mm	Maximum equivalent activity Ci	Maximum output at 1 m R/h
Cobalt, Co-60	1.35	1x1 2x2 3x3 4x4	1.3 8 30 100	1.76 10.80 40.5 135
Caesium, Cs-137	0.33	3 6x2 6x5	0.3 5 10	1.0 1.65 3.3
Iridium, Ir-192	0.48	0.5x0.5 1x1 1.3x1.3 2x2 3x3 4x4	1 6.7 12 40 110 200	0.48 3.22 5.76 19.2 52.8 96.0
Thulium, Tm-170	0.0025	0.5x0.5 1x1 2x2 3x3	1 5 15 35	0.0025 0.0125 0.0375 0.0875
Ytterbrium, Yb-169	0.125	1x1	3.5	0.44

Further details about gamma radiography sealed sources are given on fig. 26. This figure shows capsules as well as their tags. On request, capsules can be supplied without tags.

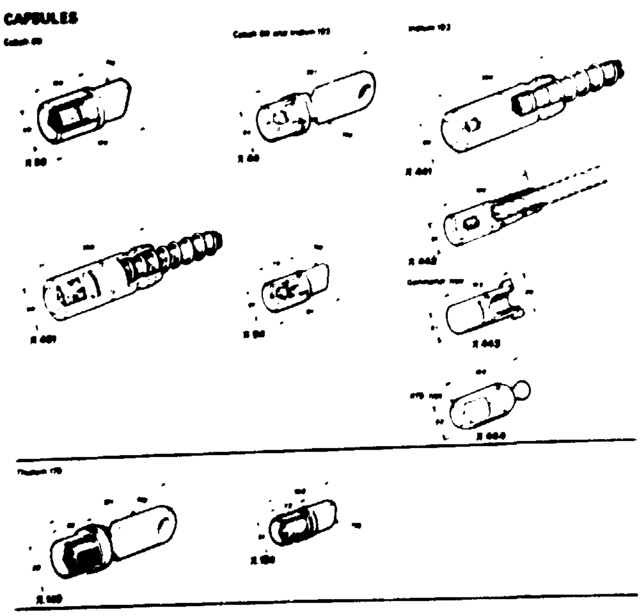


Fig. 26. Gamma radiography sealed sources (capsules with tags)

Two typical source holders are shown on fig. 27.

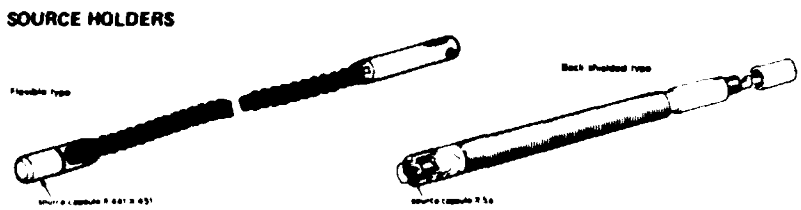


Fig. 27. Source holders

Those examples of gamma radiography sealed sources are quoted from the gamma radiography source catalogue of The Radiochemical Centre, Amersham, England.

It will be interesting to compare these outputs with these of X-ray machines (quoted in table 4).

Table 9 gives a further simplified comparison of the advantages and disadvantages of using X-rays and gamma-rays for radiography.

Table 9. Advantages and disadvantages of using X-rays or gamma-rays

	X-rays	Gamma-rays
Power supply	Electrical supply either from the mains or from a generator is required. Battery-operated units are being developed.	No power supply is necessary. Some protective containers are electrically operated, however
Supervision safety	The meters on the control box must be controlled during the exposure time; minor adjustments have to be made.	No supervision is needed other than for safety purposes.
Weight and dimensions	The apparatus is large and relatively heavy in weight.	The radiation source with its protective container can be relatively light in weight. Execeptions are cobalt-60 sources, in particular those used for heavy material thickness (>100mm), which require heavy protective containers
Manipulation	Setting-up time is considerable; sometimes it is difficult to set up the equipment.	Relatively simple in positioning and transport (except large cobalt-60 sources)
Radiation safety	Danger only during exposure, but the dose rate is relatively high during that time.	Continuous danger of radiation; the sources must also be supervised during transport, storage etc.
Radiation	Can be adjusted according to requirements by varying the kilovoltage (kV).	No adjustment is possible with a particular source. There is a limited choice of suitable radioisotopes.
Focal Spot	No important differences; radioactive sources are also obtainable in very small sizes.	

	X-rays	gamma-rays
Beam shape	Usually 60° cone perpendicular to the longitudinal direction of the tube. Special tubes are available, e.g. rod anode tubes.	Radiation is emitted in all directions For safety reasons, the radiation must be shielded in the undesirable directions
Esposure time	Short exposure times possible in normal thickness range	Generally longer exposure times (up to some hours).
Contrast of the radiograph	Radiation energy can be chosen in relation to the wall thickness.	The choice in radiation energy is very small and, as a consequence, the contrast is nearly always lower than with X-rays.
Cost of equipment	Initial costs high, repair and maintenance relatively high, in particular for field work.	Initial costs lower; repair and maintenance considerable. Costs to comply with legal regulations regarding radiation hazards are high.

10. APPARATUS FOR GAMMA RADIOGRAPHY

10.1. Design principles

Specifications for the construction of apparatus for gamma radiography are given in the ISO/DIS 3999 Draft International Standard.

This International Standard specifies the constructional requirements of portable, mobile and fixed apparatus for gamma radiography of the following categories designed to allow the controlled use of radiation for industrial purposes:

a) Category 1; Shutter type: An exposure container from which the sealed source is not removed for exposure. The beam of radiation is exposed by opening a shutter or rotating the sealed source within the container or by other means. (See fig. 28).

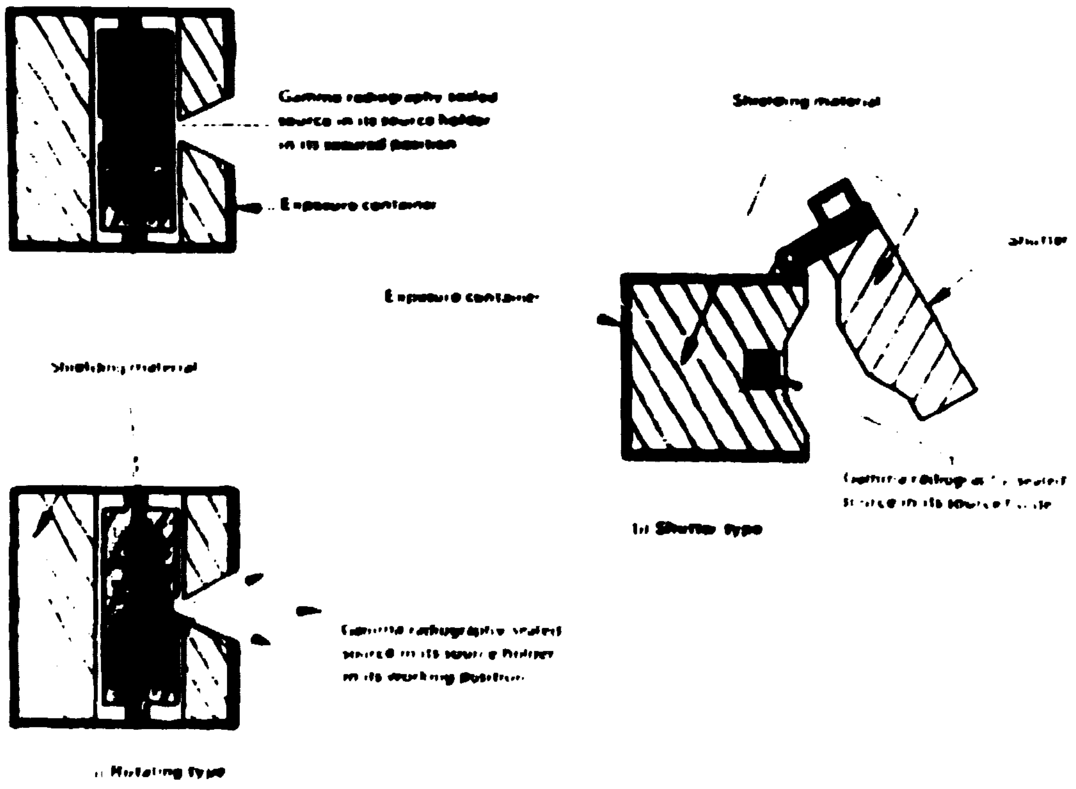


Fig. 28. Category 1 apparatus for gamma radiography

b) Category 2; Projection type: An exposure container from which the sealed source is projected out of the container through a projection sheath to the exposure head for exposure, either mechanically, electrically, pneumatically or by other means by an operator at a distance from the exposure head. (See fig. 29).

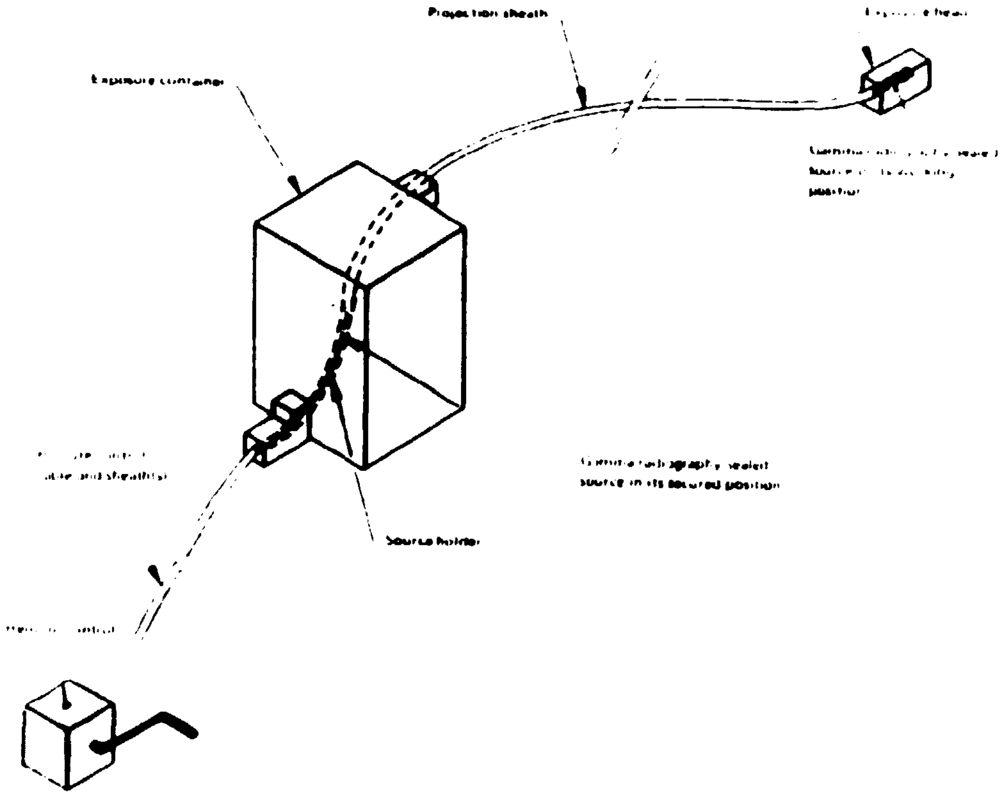


Fig. 29. Category 2 apparatus for gamma radiography

In the ISO 3999 standard the following definitions are used:

- apparatus for gamma radiography: An apparatus including an exposure container and accessories designed to enable radiation emitted by a sealed source to be used for industrial radiography.
- exposure container: A shield in the form of a container designed to allow the controlled use of gamma radiation and employing one or more gamma radiography sealed sources.
- maximum rating: the maximum activity, expressed in curies,

of a gamma radiography sealed source specified for a given radionuclide by the manufacturer and marked on the exposure container, and not to be exceeded if the apparatus is to conform to this International Standard.

- remote control: A device enabling the gamma radiography sealed source(s) to be exposed at a distance.
- projection sheath: A flexible or rigid tube for guiding the source holder from the exposure container to the working position and comprising the necessary connections between the exposure container and the exposure head.
- exposure head: A device which locates the gamma radiography sealed source in the selected working position.
- secured position: Condition of the exposure container and gamma radiography sealed source when the source is fully shielded and the exposure container is rendered inoperable by locking and/or other means.
- working position: Condition of the apparatus for gamma radiography when the beam is emitted for radiography.

According to the ISO Standard an apparatus for gamma radiography is classified according to the mobility of the exposure container:

Class P: A portable exposure container, designed to be carried by one man alone.

Class M: A mobile but not portable exposure container, designed to be moved easily by a suitable means provided for the purpose.

Class F: A fixed installed exposure container or one with mobility restricted to the confines of a particular working area.

An exposure container shall be made in such a way that when locked in the secured position and equipped with sealed sources corresponding to the maximum rating, the exposure rate does not exceed the limit in column (4) and one or other of the limits in columns (2) and (3) of table 10.

Table 10. Exposure rate limits for exposure containers

1	2	3	4
Class	Maximum exposure rate, mR/h		
	On external surface of container	50 mm from external surface of container	1 m from external surface of container
P	200 or	50	2
M	200 or	100	5
F	200 or	100	10

The ISO Standard contains further requirements regarding safety devices, source holder security and handling facilities. They are as follows:

Safety devices. Locks. On an exposure container, a series of beam emissions of source projections shall be possible only after a manual unlocking operation.

An exposure container shall be provided either with an integral lock and key or with hasps through which a separate padlock can be fitted. The lock shall be either of the safety type, i.e. lockable without the key, or an integral lock from which the key cannot be withdrawn when the container is in the working position. The lock shall retain the sealed source in the secured position and shall not, if the lock is damaged, prevent the sealed source when it is in the working position from being returned to the secured position. It a separate padlock is used, there shall be an additional device to provide a positive means of retaining the sealed source in the secured position.

Source position indicators. An apparatus for gamma radiography shall clearly indicate whether the sealed source is in the secured or the working position. If colours are used, green shall only indicate that the source is not in the secured position, but colours shall not be the sole means of indication.

Source holder security. The source holder shall be designed in such a way that it cannot release the sealed source accidentally, and shall provide it with positive retention and mechanical protection.

Handling facilities. Portability. A class P exposure container shall be provided with a carrying handle. A class M container shall be provided with a lifting device. Such a handle or device shall be adequate for its purpose and so secured that it cannot be accidentally parted from the container. (Such an adjunct is optional for a class F container.)

Mobility. The method provided for moving a class M exposure container shall have a turning circle of 3 m or less, and shall be fitted with an immobilizing device.

Special requirements regarding the marking of containers are:

Marking. All containers. Each exposure container or a metal plate permanently fixed to the container shall be permanently and indelibly marked by engraving, stamping or other means with the following:

a) the basic ionizing radiation symbol complying with ISO 361;
b) the word "RADIOACTIVE" in letters not less than 10 mm in height;
c) the maximum rating of the container:
   - for a cobalt-60 source, shown as "Rating x Ci ^{60}Co";
   or
   - for a caesium-137 source, shown as "Rating x Ci ^{137}Cs";
   or
   - for an iridium-192 source, shown as "Rating x Ci ^{192}Ir";
d) the number of this International Standard, "ISO 3999", to signify compliance with this International Standard; this ISO marking indicates the manufacturer's claim that the exposure container and its accessories conform to this International Standard; this claim shall be stated in the manufacturer's literature;
e) the manufacturer's type and serial number.

Class M and F containers. A class M or F exposure container shall be marked with the mass of the container without removable accessories.

Identification of the Sealed Source in the Container. Provisions shall be made for the attachment to the exposure container by the user of a plate giving the following information:

a) chemical symbol and mass number of the radionuclide;
b) activity and the date on which this activity was measured;
c) identify number of the sealed source.

Not all apparatus to gamma radiography are covered by the ISO standard; e.g. apparatus operated by removing the sealed source from the exposure container on a handling device is not covered by this International Standard because its use is prohibited in the national regulations of some countries. Such gamma radiography apparatus is still used for pipeline radiography because its simple construction and easy operation. It can, however, be dangerous if used by a careless operator. Fig. 33 shows the principle of such an apparatus (called "torch" type). The exposure and transport containers are designed as a single unit. The upper part, in which the source is located, can be removed by a handle screwed into its top and positioned directly on the pipe in a suitable holder. This operation can be done in a few seconds, which is the reason for the use of this equipment.

10.2. Radiation shielding

The exposure containers used in gamma radiography machines must be so designed as to provide shielding for gamma radiation from the source within. Lead, tungsten and depleted uranium are used as shielding materials. Lead is cheapest and easiest to fabricate and is therefore most commonly used for shielding. If the container is to be relatively light-weighted and small, depleted uranium is used. The thickness of the radiation shield must be such as to comply with the requirements laid down in table 10.

Knowing the maximum rating (maximum activity of the source to be used in the container) of the gamma radiography machine, one can calculate the necessary thickness of the shielding. For this purpose use may be made of the shielding data presented in fig. 30 for Co-60, in fig. 31 for Ir-192 and in fig. 32 for Tm-179.

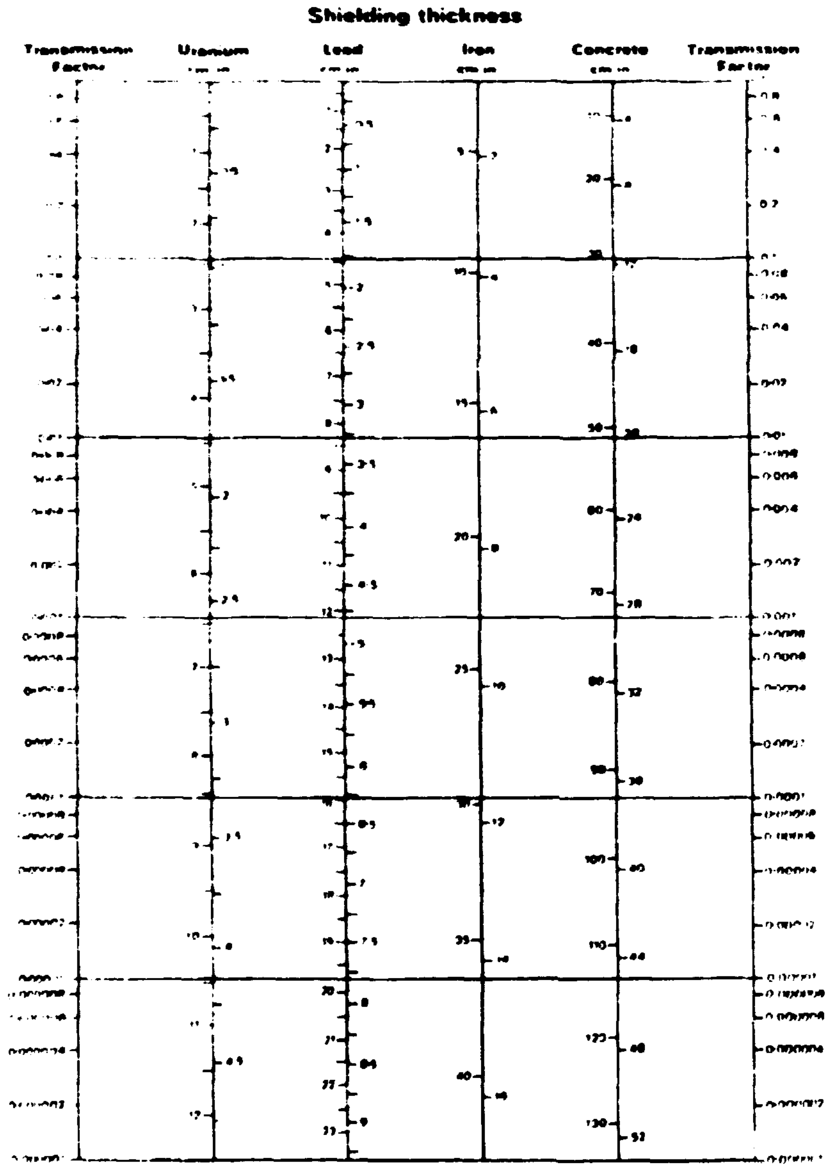


Fig. 30. Shielding data for Co 60

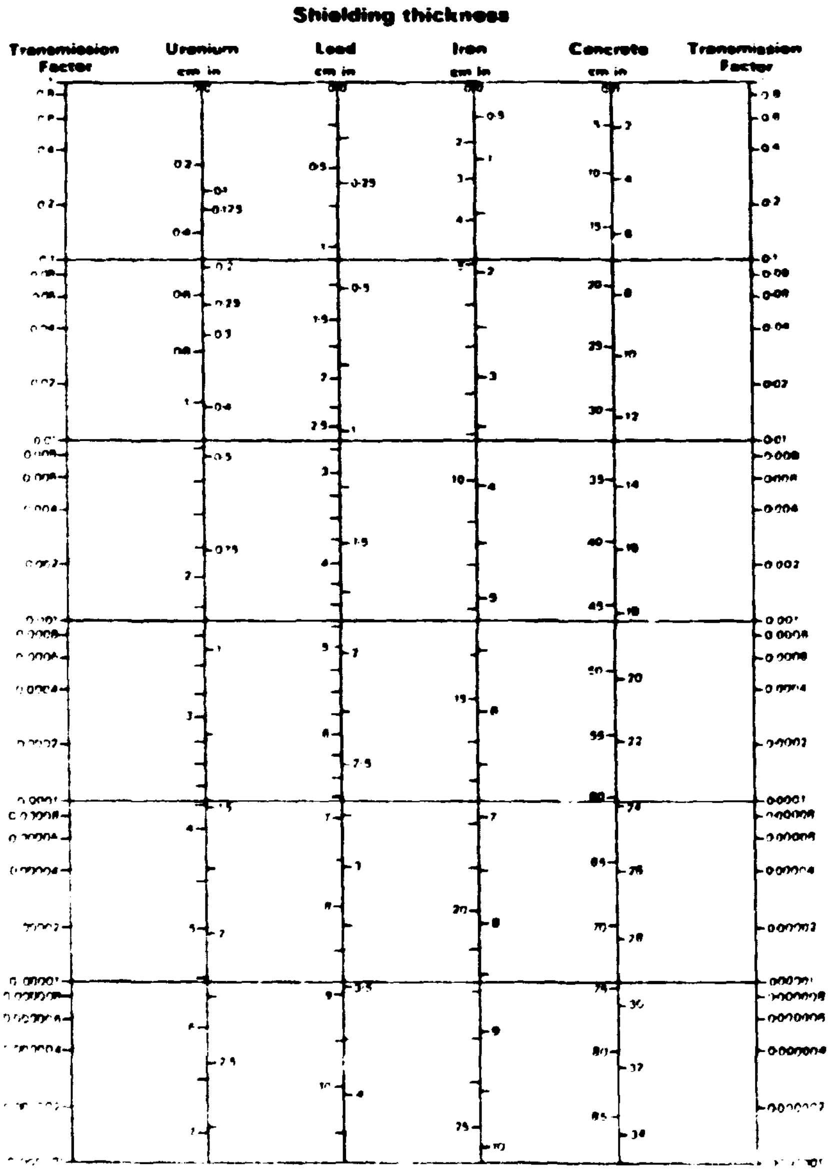


Fig. 31. Shielding data for Ir 192

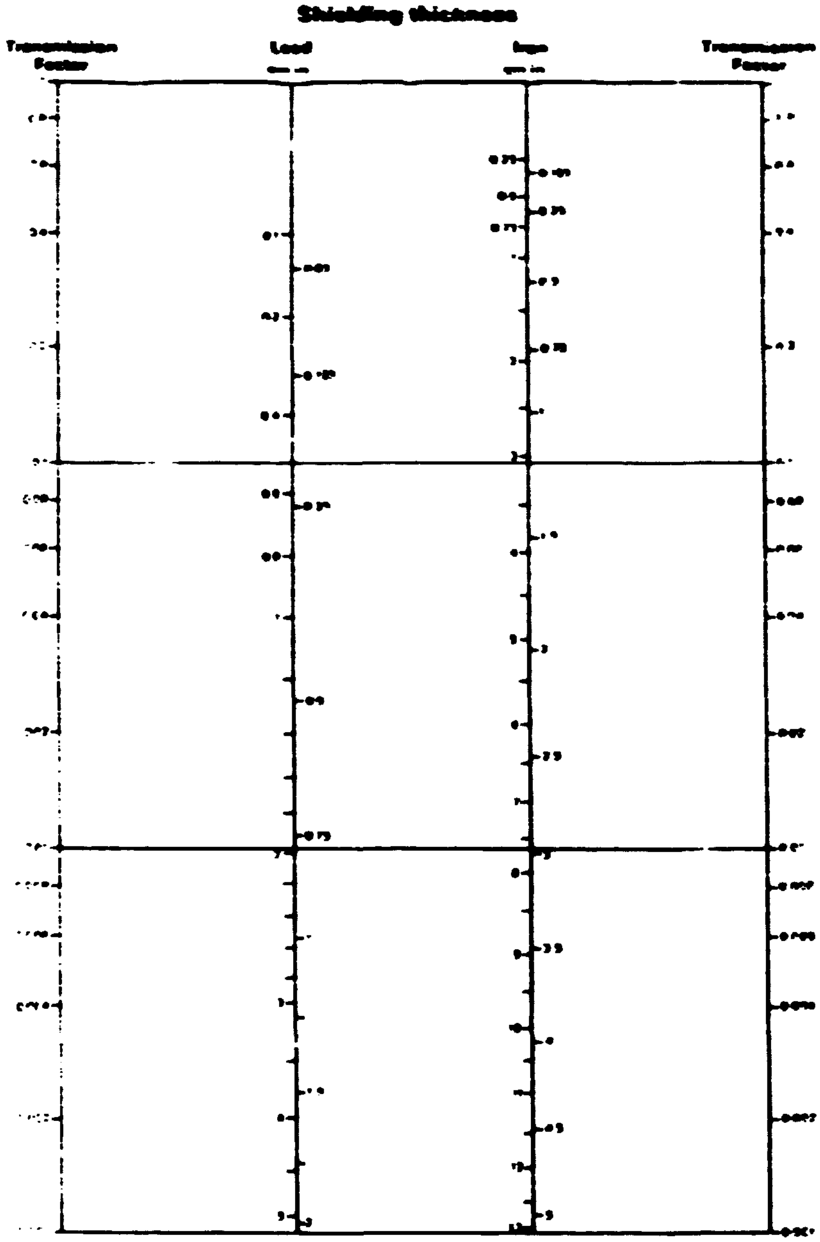


Fig. 32. Shielding data for Tm 170

First, the transmission factor must be calculated. The transmission factor is the relation between the exposure rate given in column 4 of table 8 at 1 m from the external surface of the container and the exposure rate at this distance from an unshielded source of maximum rating.

Let us consider a 200 Ci Ir-192 source to be shielded by lead or uranium. The transmission factor for such a source can be calculated as follows. Not knowing beforehand how thick the shielding will be, let us assume a 10 cm thickness in the first instance. Thus the distance between the source and a point located 1 m from the external surface of the container (as required by table 8) will be 1.1 m. According to table 3, a 1 Ci Ir-192 source will give 0.48 R/h at 1 m distance. For 200 Ci and 1.1 m, the exposure rate will be:

$$\frac{0.48 \times 200}{(1.1)^2} = 79.5 \text{ R/h} .$$

This is to be reduced to 2 mR/h for a class P (portable) exposure container. So the transmission factor is:

$$\frac{0.002}{79.5} > 0.000025 .$$

From fig. 31 one can read the necessary thickness of lead as 8 cm and 4.8 cm for uranium.

According to table 8, a 200 Ci Ir-192 source will have 4 x 4 mm dimensions. The external diameter of such a source (see fig. 26) will be 6.6 mm and we can assume that the internal cavity of the container will have a diameter of 10 mm.

Let us now check if the other shielding conditions listed in columns 2 and 3 of table 10 are fulfilled.

The exposure rate at the surface of the container made of:

lead (diameter 17 cm) — uranium (diameter 9.6 cm)

will be:

$$\frac{0.48 \times 200 \times 0.000025}{0.085^2} = 0.33 \text{ R/h} = 330 \text{ mR/h} \qquad \frac{0.48 \times 200 \times 0.000025}{0.048^2} = 1.04 \text{ R/h} = 1040 \text{ mR/h}$$

In both cases these exposure rates are greater than the prescribed 200 mR/h, and therefore the thickness of the shielding must be increased.

By increasing the lead shield thickness to 9 cm, one finds a transmission factor of 0.000008 and hence the exposure rate at the surface of the container of:

$$\frac{0.48 \times 200 \times 0.000008}{0.095^2} = 0.085 \text{ R/h} = 85 \text{ mR/h} < 200 \text{ mR/h}$$

and at 5 cm distance from the surface of:

$$\frac{0.48 \times 200 \times 0.000008}{0.145^2} = 0.036 \text{ R/h} = 36 \text{ mR/h} < 50 \text{ mR/h} .$$

For uranium, the necessary thickness will be 5.75 cm, giving a transmission factor of 0.0000075 and an exposure rate at the surface of:

$$\frac{0.48 \times 200 \times 0.0000075}{0.0625^2} = 0.185 \text{ R/h} = 185 \text{ mR/h} < 200 \text{ mR/h} .$$

At 5 cm from the surface of the container, the exposure rate will be:

$$\frac{0.48 \times 200 \times 0.0000075}{0.1125^2} = 0.56 \text{ R/h} = 56 \text{ mR/h} \simeq 50 \text{ mR/h}.$$

It would be interesting to compare the weights of these two containers. Assuming that they are made as spheres, one finds the following weights: 29 kg for lead and only 20 kg for uranium. As can be seen, the use of depleted uranium not only reduces the thickness of the shielding, and hence the overall dimensions of the container, but also its weight.

10.3. Practical solutions

The "torch" type apparatus was already shown in fig. 33. As mentioned before, it is not recommended by international standards, and is prohibited by many national regulations. This type of apparatus is designed for relatively small activities of gamma ray sources.

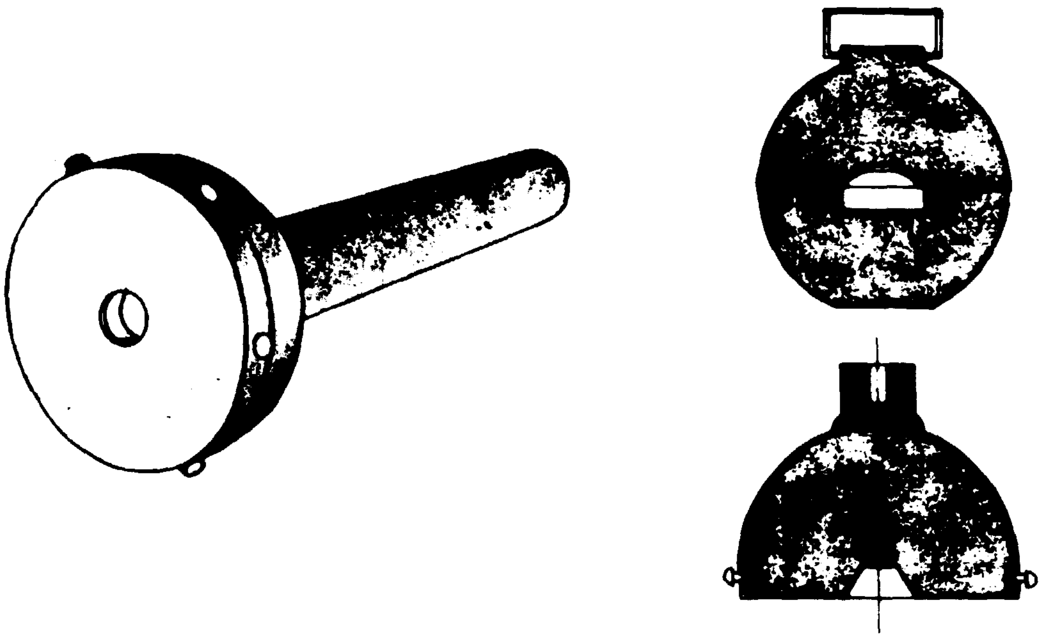


Fig. 33. "Torch" type gamma radiography machine

The <u>opening-shutter-type</u> machine, shown schematically in fig. 28a, usually gives a conical beam of gamma radiation when the shutter is open (fig. 34). Fig. 35 gives a cross section diagram

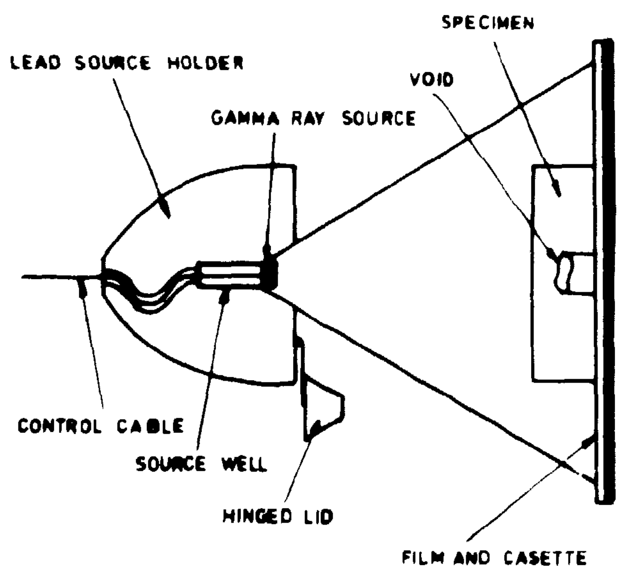


Fig. 34. Conical beam of gamma rays

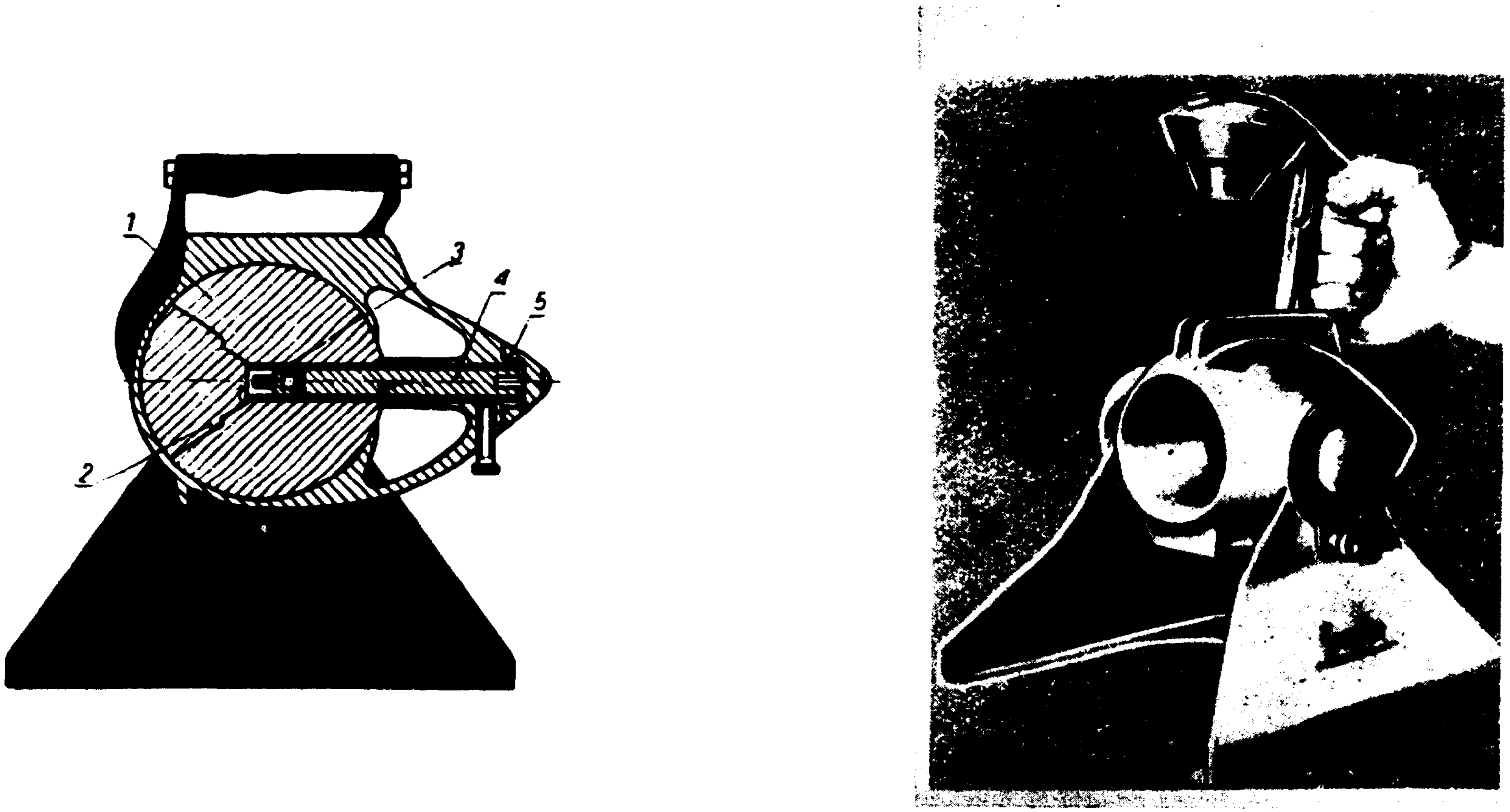


Fig. 35. Opening-shutter-type gamma radiography machine

1 - lead shield

2 - lead shutter

3 - radiation source

4 - source holder

5 - source securing device

of such a machine as well as its photograph. Machines of this type very often have a possibility of ejecting the radiation source from the container at a small distance (see fig. 36) to permit panoramic radiography, as shown schematically in fig. 37.

Fig. 36. Panoramic exposure with the shutter-type machine

This is possible by attaching, from behind the container, an ejecting mechanism connected to the source holder. This mechanism is steered by a crank through a flexible cable (as shown in fig. 37).

The described machine works as follows. In the "off" position the mobile shutter is closed (as in fig. 35a) and locked. After positioning (aiming the machine at the object to be radiographed) the shutter is unlocked and opened (as in fig. 35b). After the exposure is terminated, the shutter is closed and locked. For panoramic exposures the rear cover of the machine (5 in fig. 35a) is removed and the ejecting mechanism is con-

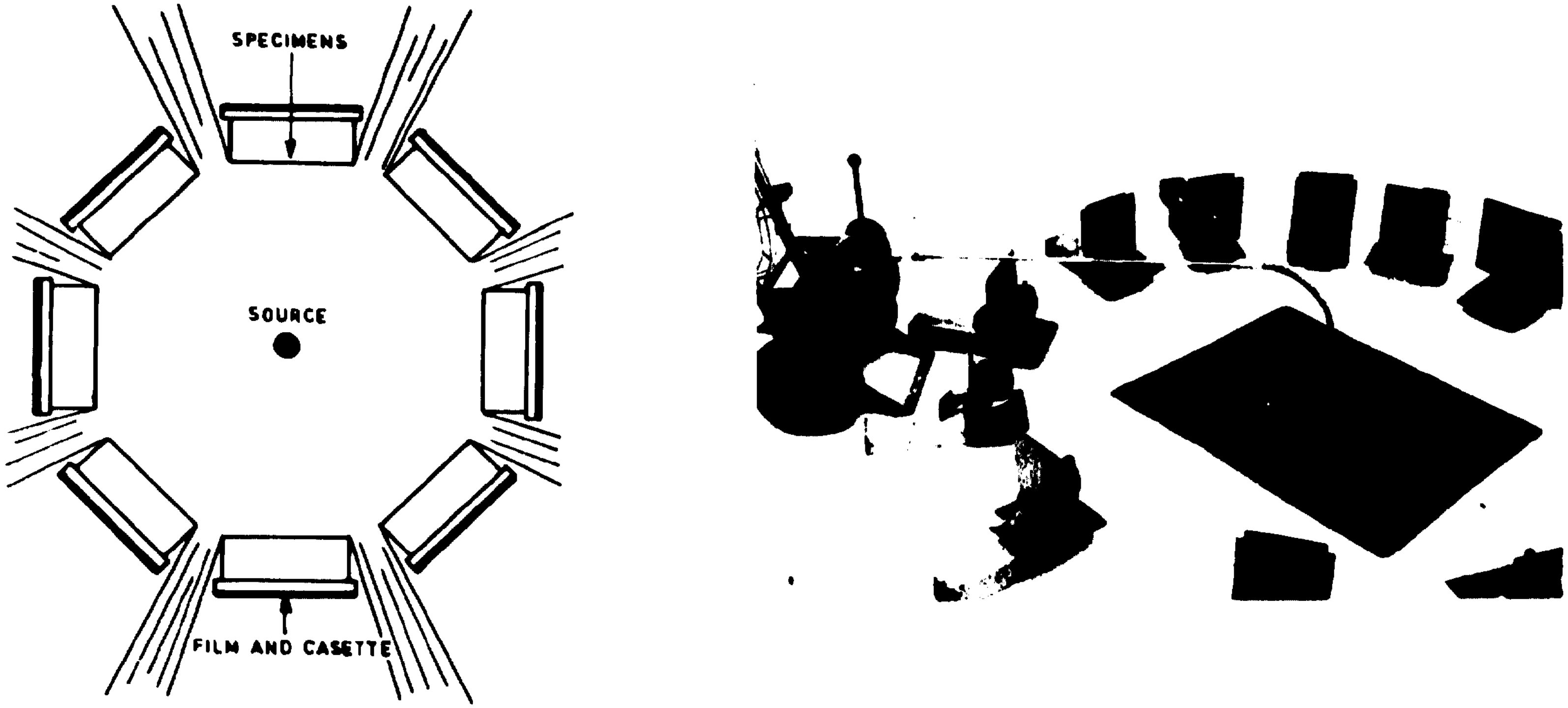


Fig. 37. Arrangement for panoramic radiography

nected to the source holder (4). The screw holding the source holder in position is released, the shutter opened and the source can be pushed out of the container by the operating crank (seen at the bottom left of fig. 36). After terminating the exposure, the source is removed in reverse sequence to its "off" position and the shutter is closed and locked.

The opening-shutter-type gamma radiography machines are usually designed to accommodate gamma ray sources of small or medium activities.

The rotating-shutter-type machine (shown schematically in fig. 28) is used for radiation sources of all activities. A practical design of this type of machine is shown in fig. 38 in cross section (gamma ray source in "off" position). By rotating the inner uranium cylinder 180°, the container will be in its working position (the radiation source (5) will be opposite the opening in the shield). This can be done either by rotating the dust cup (6), or can be done remotely if the dust cup is removed and a flexible shaft connected to the rotor shaft (7).

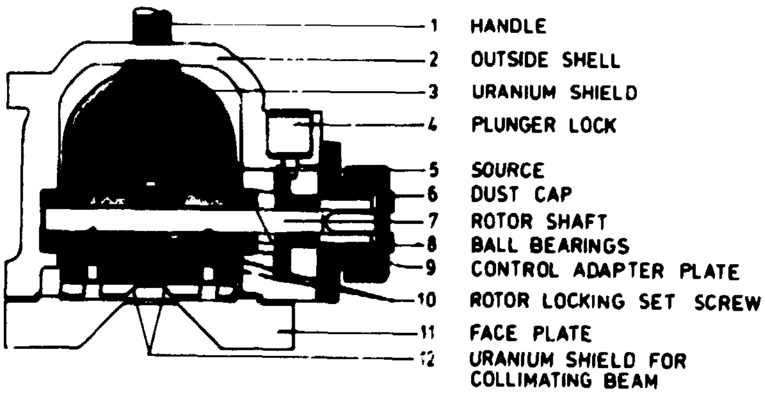


Fig. 38. A rotating shutter type gamma radiography machine

This rotating-shutter-type principle is used in many types of gamma radiography machines. Figs. 39 and 40 show a 750 Ci Co-60 machine (in fig. 40 the machine is shown with a smaller aiming device connected to it).

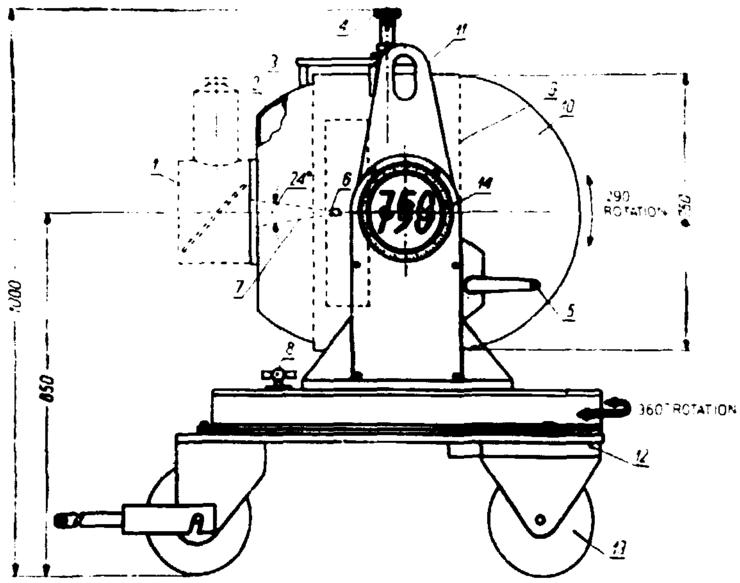


Fig. 39. A 750 Ci Co 60 gamma radiography machine

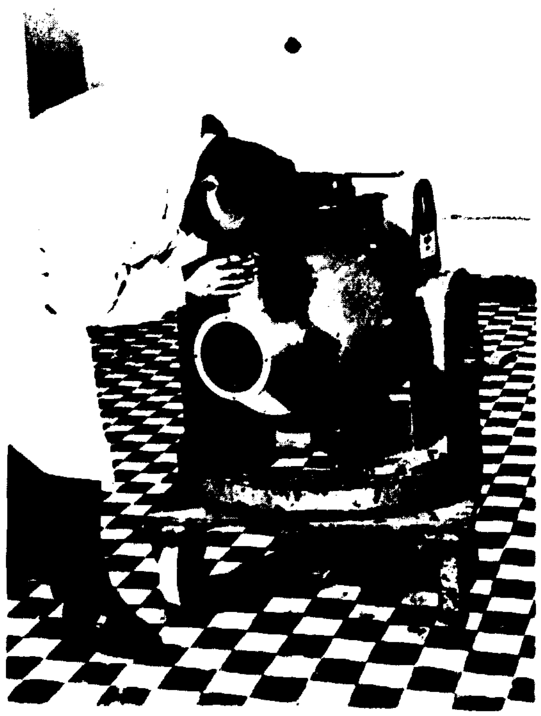


Fig. 40. A 750 Ci Co 60 gamma radiography machine with an aiming device

A <u>projection-type</u> gamma radiography machine (shown schematically in fig. 29) is shown in fig. 41 in three positions of the

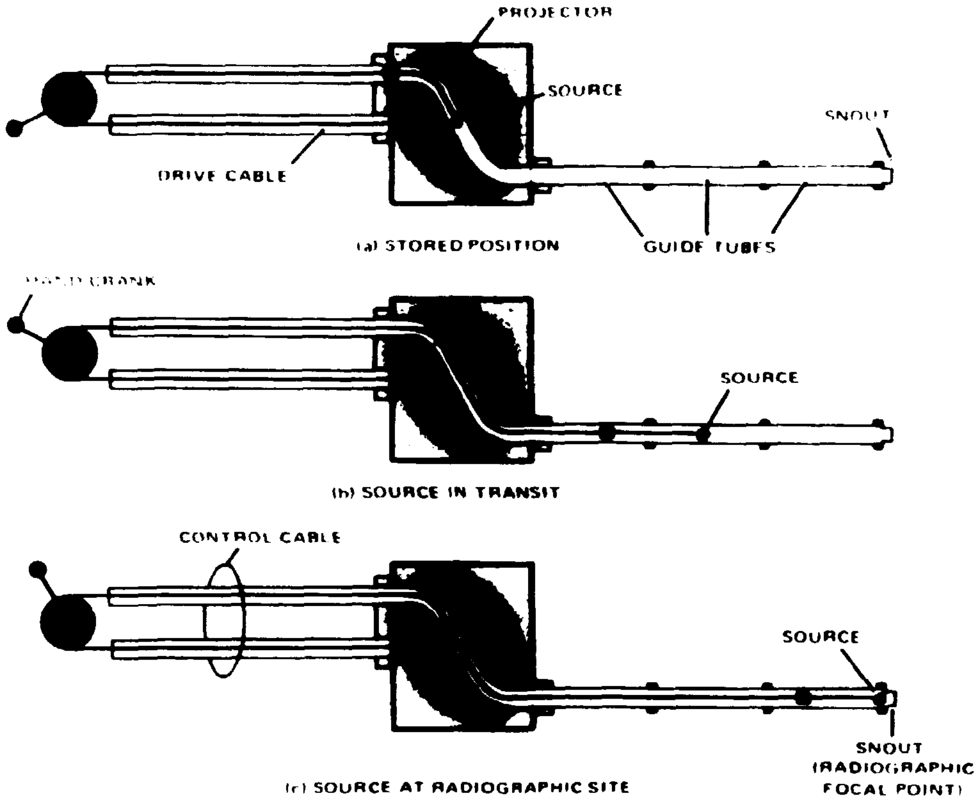


Fig. 41. A projection type gamma radiography machine

source: the source stored, in transit and at working position. To project the radiation source from the container (fig. 42),

Fig. 42. A projection type gamma radiography machine

special flexible control cables are used. These cables are connected to the source holder (see fig. 43) from one side of the

Fig. 43. Attaching the control cable to the source holder

container and from the other side a projection sheath is connected (fig. 44) through which the source can travel at a predetermined distance (even up to 15 m).

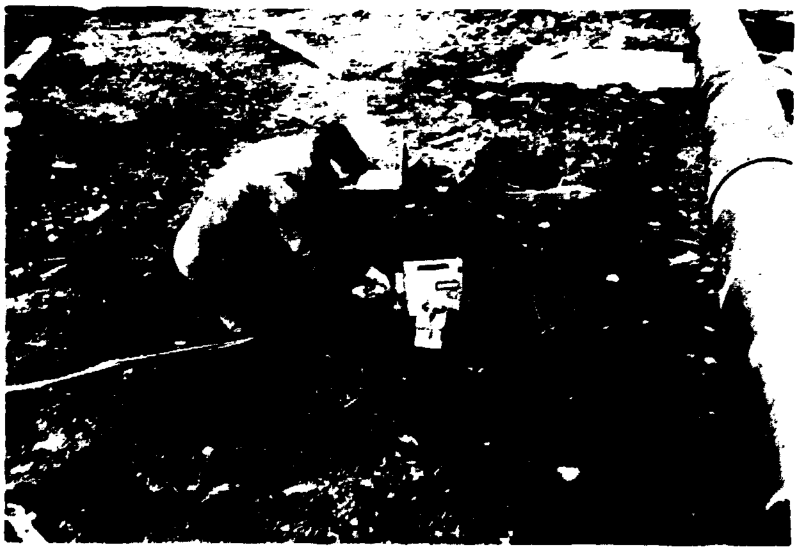


Fig. 44. Attaching the projection sheath to the working container

To perform radiography with the projection-type radiography machine, exposure heads are used. They serve to locate the gamma ray source in the selected working position and at the same time they can provide collimation of the gamma ray beam. Fig. 45 shows such collimators for directional radiography (as in fig. 46) or for panoramic radiography (fig. 47).

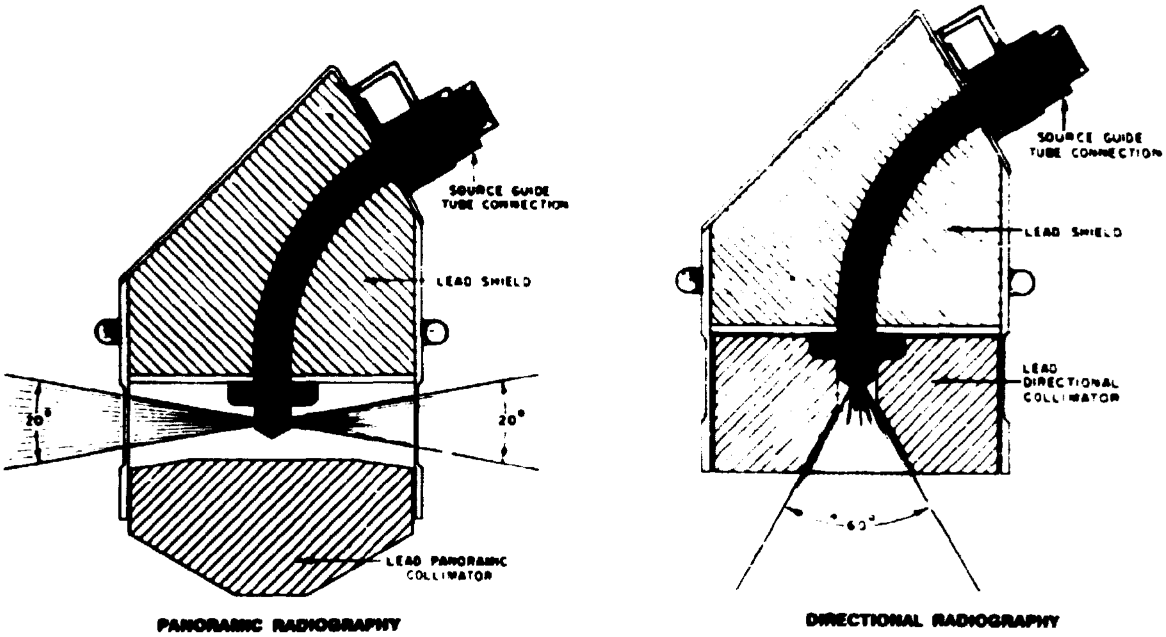


Fig. 45. Collimators for directional and panoramic radiography

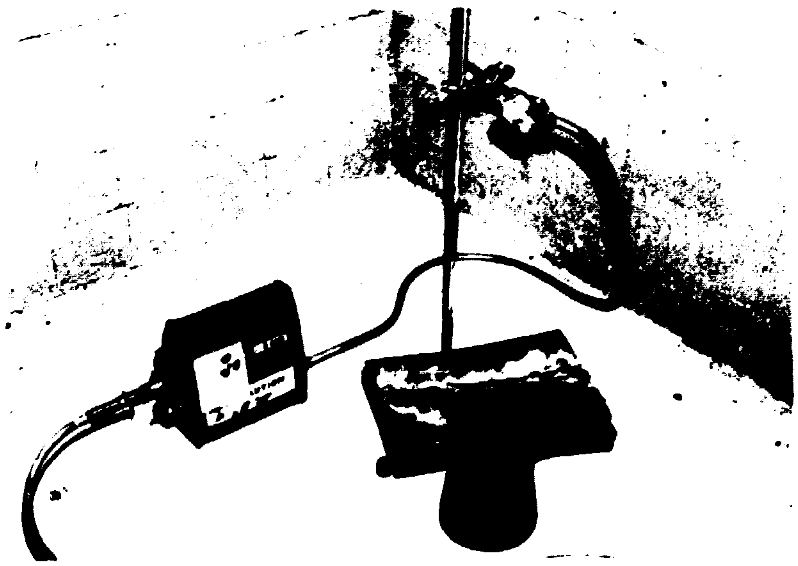


Fig. 46. Directional radiography

Fig. 47. Panoramic radiography

Many gamma radiography machines combine the rotating shutter with the source projection principle. In these machines (of which fig. 48 shows a cross section) the source is not connected to the rotating shutter itself but to the projection cable. In the "off" position the shutter closes the container. The source is at the same time protected from the projection cable side by the source holder which contains some flexible shielding mate-

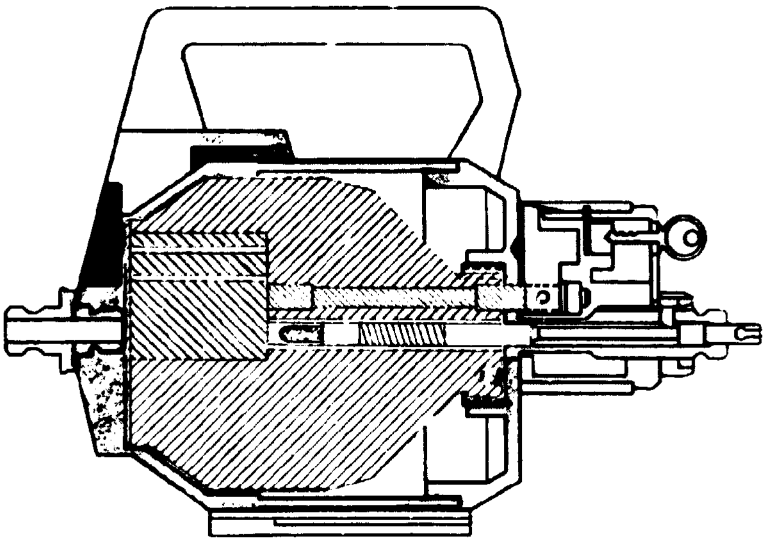


Fig. 48. Rotating-shutter-with-source-projection machine (cross section)

rial. To such a machine (fig. 49) a remote control cable is con-

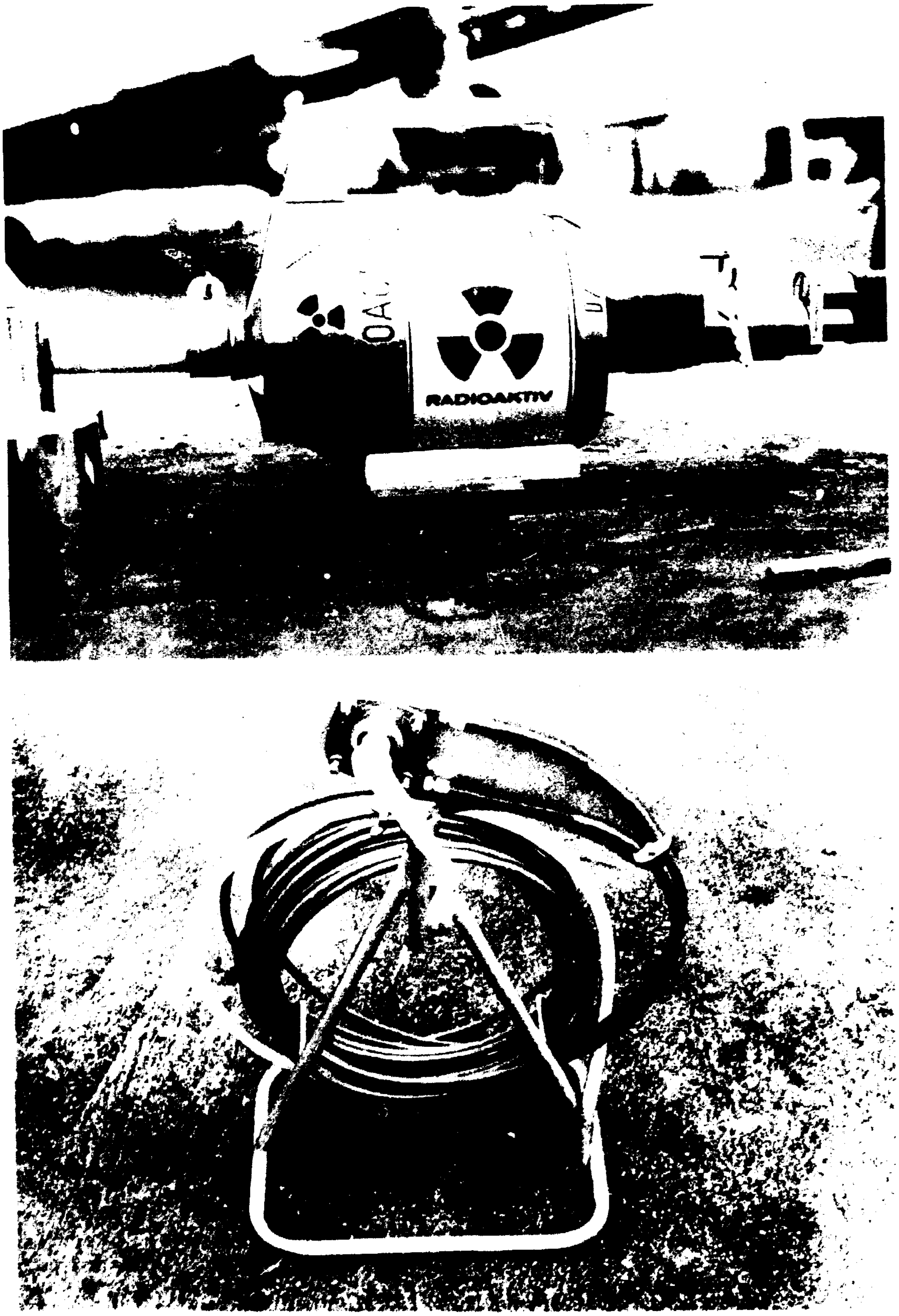
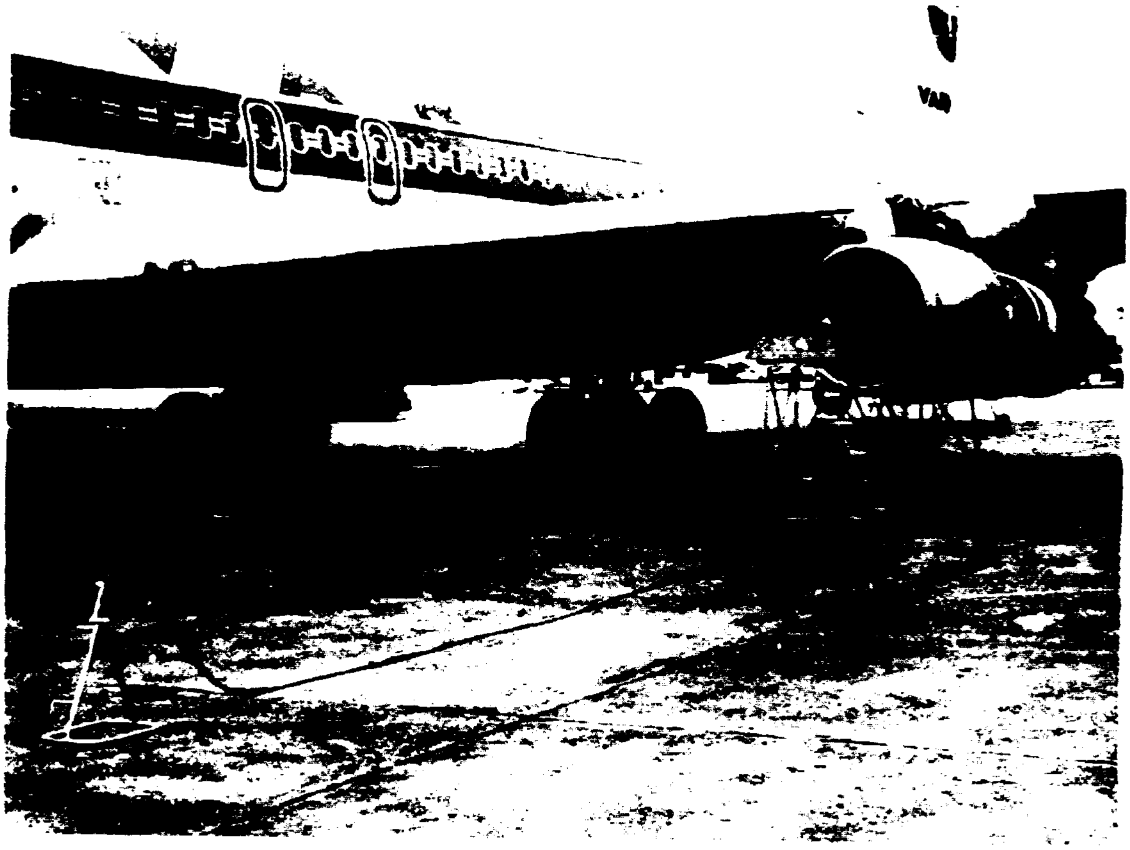
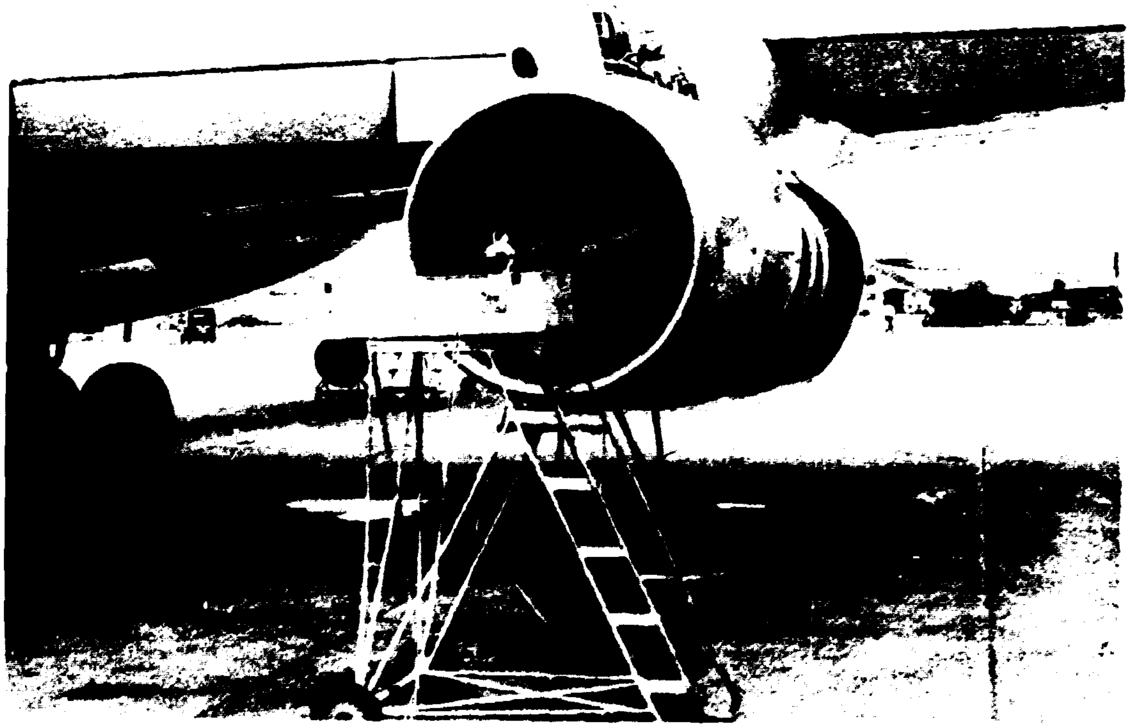


Fig. 49. Rotating-shutter-with-source-projection machine (view)





nected to the source holder from one side and a projection sheath from the other side. With both projection types of gamma radiography machines, rigid projection sheaths can be used. Such rigid sheaths are used as aluminium tubes. Several such tubes can be screwed together. These rigid sheaths are used mainly without collimators for panoramic exposures (see fig. 50).

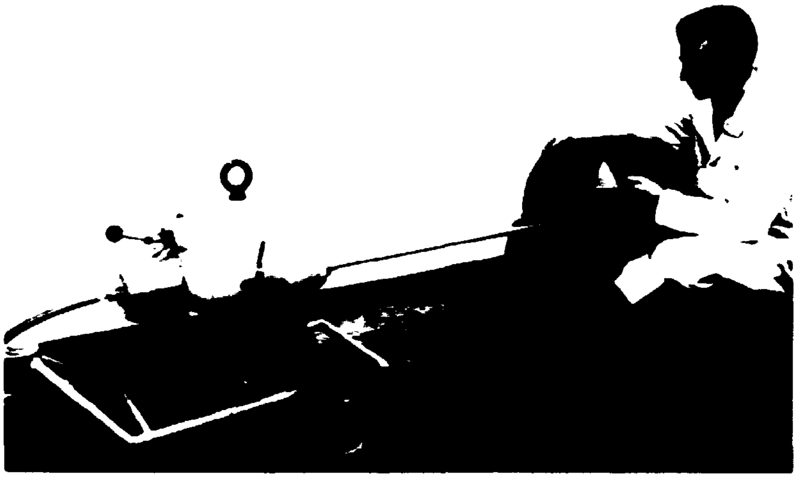


Fig. 50. Panoramic exposure with rigid sheath

In both types of the source projection machines the source can be moved through the projection sheath using either a remote control operated by a hand crank (seen in fig. 47) or by an electric driven mechanism. Such an electrical remote control unit can incorporate a timer which, after the predetermined time of exposure, will pull back the source from the working to the "off" position.

A special category of gamma radiography machines is used for the weld inspection on pipelines. These are the so-called pipeline crawlers. These machines (fig. 51) can be introduced inside a pipeline and due to their battery-operated drives can travel inside a pipeline at a distance of up to 2 km. Crawlers have remote (wireless) control by means of which the source is automatically pushed out in the working position when the crawler has reached the circumferential weld on the pipeline to be examined. The crawler is stopped by a small radioactive source placed on the outside of the pipeline near the weld, the panoramic exposure

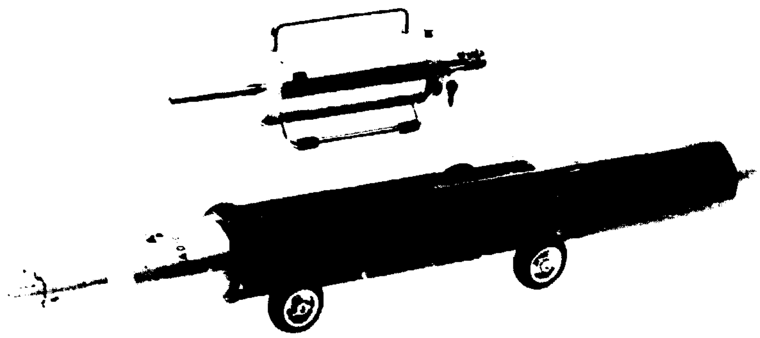


Fig. 51. Pipeline crawler

is made, the source is retracted to the "off" position and the crawler can travel to the next weld. After finishing the job, the crawler can return back through the pipeline (also by remote control) where it is removed from the pipe.

11. RADIOGRAPHIC INSPECTION

The main field of application of X-rays and gamma-rays in NDT is the radiography of weldings and castings. In various international and national standards recommendations can be found related to the radiographic inspection of weldings and castings. As it is not the aim of this presentation to give detailed instructions on how to perform gamma radiography, only some general recommendations will be given regarding radiography of welds. They are extracted from international ISO recommendations. International recommendations for castings do not exist.

11.1. General requirements

According to ISO recommendations:

- R 947: "Recommended practice for radiographic inspection of circumferential fusion welded butt joints in steel pipes up to 50 mm (2 in) wall thickness".
- R 1106: "Recommended practice for radiographic inspection of fusion welded butt joints for steel plates up to 50 mm (2 in) thick".
- International Standard 2405: "Recommended practice for radiographic inspection of fusion welded butt joints for steel plates 50 to 200 mm thick".

the radiographic techniques are divided into the following three classes:

Class A: general technique for X-ray examination;
Class B: more sensitive X-ray technique;
Class C: general technique for gamma-ray examination.

Class A

Most cases, in particular where mild or low alloy steel is concerned, are covered by the correct use of the technique given for Class A.

Class B

Class B (high-sensitivity X-ray examination) is intended only for more important and difficult cases, or where the Class A technique is unlikely to reveal the imperfections sought. It is a technique in which only fine-grain films and lead screens are used; it therefore requires longer exposure times and, on occasions, the use of equipment capable of giving voltages higher than those required for Class A.

Class C

With regard to Class C (gamma-ray examination) it is to be noted that the detectability of imperfections obtainable even with the best gamma-ray technique is always inferior to that obtainable with the Class A technique. The use of gamma-rays should, therefore, be limited as far as possible to cases in which the shape, the thickness or the accessibility of the weld renders X-ray inspection impossible. It should be mentioned in the test report that gamma-rays have been used and full details of the source should be given.

It should be noted that the known disadvantage of the Class C technique (low contrast) is sometimes offset by the fact that the small size of the radioactive sources allows of their being placed on the axis of the pipe to be examined, thus ensuring the best geometrical conditions while avoiding, in many instances, the disadvantages arising from the double wall techniques.

The requirements regarding films and screens are as follows:

The following types of films and screens should be used:

Class A. According to circumstances, non-screen films may be used without screens or with lead screens. The thickness of these screens should lie within the range 0.02 to 0.15 mm.

The use of salt screens is not recommended, but if, because of unavoidable circumstances, they are used they should be of the high-definition type, and this should be mentioned in the test report, as this technique causes loss of definition.

Class B. Fine-grain, high-contrast films should be used in combination with lead screens. The thickness of these screens should lie within the range 0.02 to 0.15 mm.

Class C. Fine-grain, high-contrast films should be used in combination with lead screens. The thickness of the front screens should lie within the range 0.02 to 0.15 mm. The back screens may be of greater thickness.

The source-to-film-distance shall be chosen according to the following principles:

The distance between the film and the adjacent weld surface should be as small as possible.

The minimum target (source)-to-film distance $f_{min.}$ depends on the effective dimension d of the focal spot or source and on the distance b between the film and the surface of the specimen facing the X-ray tube or radioactive source.

The resulting geometric unsharpness or penumbra, u, can be calculated from the following formula:

$$u = \frac{bd}{f_{min.} - b}$$

It should not exceed the following values:

Class A	Class B	Class C
0.4 mm	0.2 mm	0.4 mm

The area to be taken into consideration at each exposure should be such that the thickness of the material at the extremities of the exposed area, measured in the direction of the beam incident at that point, does not exceed the actual thickness at that point by more than the following values:

Class A	Class B	Class C
10%	6%	10%

A larger target (source)-to-film distance will, therefore, generally allow the use of larger film size.

For pipes the recommendation is:

The maximum area to take into consideration at each exposure will be determined by the difference between the thickness of the material penetrated in the centre of the radiation beam and that at the extremities measured in the direction of the beam at those points. The differences in density resulting from this variation of thickness and recorded on the film should not exceed the admissible limits specified in the ISO Standard.

It should be noted that this limitation not only ensures the best utilisation of the film characteristics, but also reduces the distortion of the image at each extremity of the film.

There are also requirements regarding the density of radiographs. They are as follows:

Exposure conditions should be such that the density of the radiograph of the sound weld metal in the area under examination, including fog density, lies within the range given below:

Class A	Class B	Class C
1.7 to 3.0 for non-screen type films		
1.3 to 2.3 for screen type films for the exceptional case where this type of film is used	2.0 to 3.0	2.0 to 3.0

Higher densities may be used with advantage where the viewing light is sufficiently bright to permit adequate interpretation. Precautions should be taken to avoid glare.

For Class C, if prior agreement has been given by the inspecting authority, who in some cases will be the purchaser himself and in other cases an authority in whom consulting and inspection rights have been vested by the purchaser, the minimum density may be reduced to 1.5.

In order to avoid unduly high fog densities arising from film ageing, development, or temperature, the fog density should be checked from time to time on a non-exposed sample taken from the films being used, and handled and processed under the same conditions as the actual radiographs. The fog density should not exceed 0.2.

According to ISO/R 947 and 1106 gamma-ray sources give best results above the following thicknesses:

Ir-192 - 10 mm of steel
Cs-137 - 25 mm of steel
Co-60 - 38 mm of steel.

11.2. Inspection of circumferential welds

For the setting up of the films and of the source of radiation the ISO recommendation R 947 gives the following requirements:

Relative position of films and sources, depending on the size and accessibility of the joints:

I Film inside, source of radiation outside (see fig. 52).
The source of radiation should be placed at a distance from the weld as defined below, the axis of the cone of radiation being normal to the surface under examination at its centre.
The cassette should be placed on the corresponding area inside the pipe, in close contact with the weld.

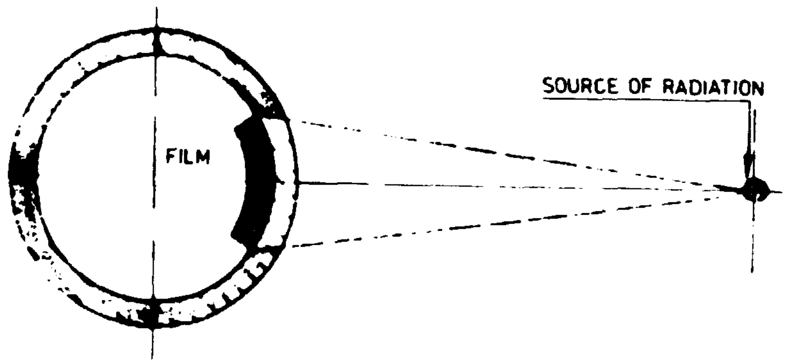


Fig. 52. Film inside, source of radiation outside

II. Film outside, source of radiation inside (see fig.53)
The source of radiation should be set up inside the pipe, on the axis of the pipe if possible, though otherwise it may be placed eccentrically in the plane of the weld, the axis of the cone of radiation being normal to the surface under examination at its centre.
The cassette should be placed on the corresponding area outside the pipe, in close contact with the weld.

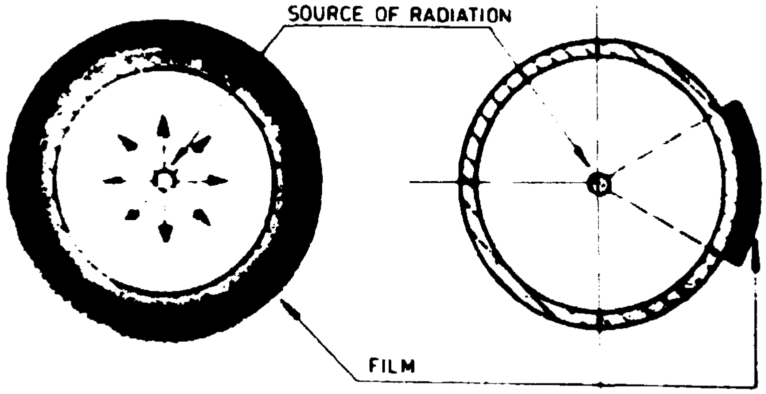


Fig. 53. Film outside, source of radiation inside

III. Film and source of radiation outside - double wall, double image (fig.54)

The source of radiation should be placed at a distance as defined below in a position so that

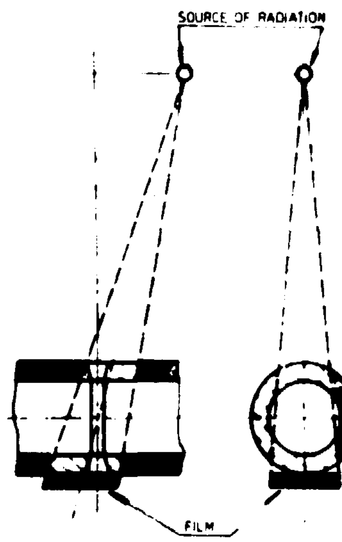


Fig. 54. Film and source of radiation outside. Double wall, double image

the axis of the cone of radiation is inclined to the axis of the pipe, and passes through the centre of the plane of the weld. The cassette containing the film, which should be of sufficient length to contain the two images of the weld, should be placed against the pipe wall further from the source, and disposed in such a manner that the axis of the cone of radiation passes through the centre.

IV. Film and source of radiation outside - double wall, single image (see fig.55)
The source of radiation should be placed so as to achieve the minimum focus-to-film distance compatible with the source size and wall thickness to be examined. If possible the souıce should be in contact with the pipe, with the radiation passing through the parent metal adjacent to the weld, but this may not be possible with small diameter pipes. The film should be placed on the side of the pipe further from the source of radiation, in close contact with the weld, the axis of the cone of radiation passing through the centre of the portion of weld under examination.

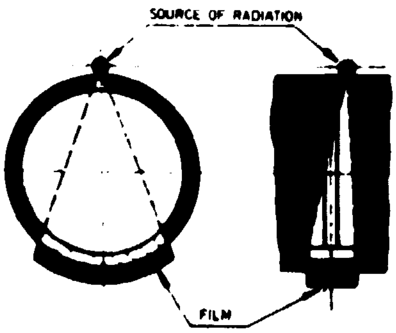


Fig. 55. Film and source of radiation outside. Double wall, single image

General guidance in the selection of the appropriate technique:

I. Film inside, source of radiation outside (fig. 52)
This technique should be used for large cylindrical bodies, where the limitation of maximum area to be examined permits the use of long films whilst keeping the focus-to-film distance within reasonable limits.

II Film outside, source of radiation inside (fig. 53)
When applicable, this technique should be considered as the most convenient, because with the source situated at or near the centre, there is no restriction regarding the area examined. For large bodies conventional equipment may be used and for small ones hollow anode X-ray tubes or gamma-ray sources are required. This technique is particularly recommended for thick pipes of small diameter.

III Film and source of radiation outside - double wall, double image (fig 54)
This technique should be used for pipes having diameters not exceeding approximately 100 mm, the necessary focus-to-film distance being too large with larger diameters; it should be noted, however, that the increase of wall thickness restricts the length of weld which can be properly radiographed.

IV Film and source of radiation outside - double wall, single image (fig. 55)
This technique will give the best results for pipes not accessible from inside, with diameters larger than approximately 100 mm. It can be used for pipes with diameters up to about 0.90 m, beyond which the source-to-film distance becomes too great.

Note-Whenever possible, in particular when a large part of the radiation beam is used for covering the area to be irradiated, it is recommended that operators should set up the equipment in such a way that the axis of the beam (inside the tube) is parallel to the pipe to be radiographed. This ensures the best image definition, even at the extremities of the film, and a more uniform distribution of the intensity of the radiation.

Besides the general requirements for the source-to-film distance given above, additional requirements are given for circumferential welds. They are as follows:

When using techniques I and II, the minimum target(source)-to-film distance should be calculated directly from the conventional formula.

When using technique III it is necessary to introduce into the formula, for b, the external diameter of the pipe instead of its wall thickness.

Below, the approximate target(source)-to-film distances are given as multiples of the external diameter for Classes A and C (penumbra, u=0.4 mm) and for Class B (penumbra, u=0.2 mm) and for different focal spot sizes.

Table 11. Minimum source-to-film distances

Class	d (Focal spot) (mm)	$f_{min.}$ (expressed as a multiple of the pipe diameter)
A and C (penumbra, u=0.4 mm)	2	5
	3	7.5
	4	10
	5	12.5
	6	15
B (penumbra, u=0.2 mm)	2	10
	3	15
	4	20
	5	25
	6	30

When using technique IV, the minimum target(source)-to film distances should be calculated by introducing into the formula, for b only, the actual wall thickness of the section of circumference under examination. It should be noted that, with technique IV, when the outside diameter of the pipe plus the actual distance between source and radiation outlet port is not less than the minimum target (source)-to-film distance required, there are no objections to putting the X-ray equipment or the radioactive source in close contact with the pipe.

11.3 Inspection of thick steel plates

For the inspection of steel plates 50 to 200 mm thick, the ISO 2405 international standard gives the following recommendations.

The steel thickness for which different types of X-ray and gamma-ray equipment is considered to be suitable is given in table 12.

Table 12. Type of equipment and thickness of steel

Group	Description of equipment	Useful thickness mm
A	X-rays: up to 400 kV	60 to 85
B (I)	X-rays: 1 and 2 MV, focus>6 mm	50 to 125 1)
B (II)	X-rays: 1 and 2 MV, focus>1 mm	50 to 125 1)
C	X-rays: linear accelerators 3 to 8 MV	70 2) to 200
D	X-rays: tetatrons and linear accelerators, 8 to 35 MV	70 2) to 200
E	Gamma-rays, Cobalt-60	50 to 150 3)
F	Gamma-rays, Iridium-192	50 to 110 3)

1) for the 2 MV equipments, the maximum thickness can be extended to 200 mm.

2) This thickness may be reduced to 60 mm if very fine-grain films are used and a density of 3 is reached.

3) The upper end of the thickness range can only be achieved with either very high strength sources or very long exposure times.

The following recommendations are given regarding type of film, intensifying screens and filters:

With equipment in groups A, B, E and F, the film used should be one of the types known as medium-speed, fine-grain or very fine-grain X-ray film. These films are usually described as "direct type", for use with metal intensifying screens, or as "non-screen" film.

With equipment in groups C and D, the film should be of the fine-grain, direct type. Medium-speed film is not normally necessary.

The film should be used in a type of X-ray cassette which ensures very good contact between the intensifying screens (or screen) and the film emulsion.

Note-With thick screens, cassettes casettes are not always satisfactory from this point of view and vacuum-type cassettes can be used with advantage.

The screen thicknesses and materials should be as follows:

Group A:
Lead foil screens: front 0.02 to 0.1 mm;
back 0.02 to 0.1 mm.

Group B:
Lead foil screens: front 0.2 to 1.0 mm;
back 0.5 to 1.6 mm.

Group C:
Copper or lead screens: front 1.0 to 1.6 mm;
back 1.0 to 1.6 mm.

Group D:
Tantalum, tungsten or lead screens: front 1.0 to 1.6 mm;
back none.

Note-Screens of tantalum or tungsten give better sensitivity.

Group E:
Copper or lead screens: front 0.2 to 1.0 mm;
back 0.1 to 0.5 mm.

Note-In place of copper or copper base alloy screens, it is possible to use screens of other materials of low atomic number and high specific density (Ni, Zn and their alloys).

Group F:

Lead foil screens: fron t 0.05 to 0.2 mm;
back 0.05 to 0.2 mm.

When gamma-ray sources are used, i.e. equipment in groups E and F, a filter may be placed between the specimen and cassette. This filter should be of lead, 1.0 mm thick with Iridium-192 sources and 2.0 mm thick with Cobalt-60 sources.

For focus-film-distance table 13 shall be observed.

Table 13. Minimum focus-film distances

Equipment group	Minimum focus-film distance (or FFD) in mm					See Notes
	Specimen thickness, mm					
	50	75	100	150	200	
A	1000	1250	-	-	-	1
B (I)	1500	1800	2000	3000	3800	
B (II)	1000	1000	1000	1250	1500	
C	-	1000	1500	1500	1500	2 and 3
D	-	-	-	-	-	4
E	500	650	750	900	-	5
F	750	900	1000	-	-	5

Notes:

1) These values are based on a focus size of 5 mm; if the focus is of a different size, the f.f.d. should be adjusted in direct proportion.

2) These values are based on a focus size of 2 mm or less.

3) If a large field coverage is required, these values may have to be increased, irrespective of the focus size, dependent on the amount of beam-flattening which the equipment utilises.

4) The s.f.d. to be used should be chosen with regard to the

length of the weld to be radiographed in one exposure and the beam-flattening of the equipment.

5) These values are based on a source diameter of 4 mm; for other sizes they should be adjusted in direct proportion, with a minimum value of 250 mm s.f.d.

IQI sensitivity values for different types of equipment quoted in table 12 are given on fig. 56.

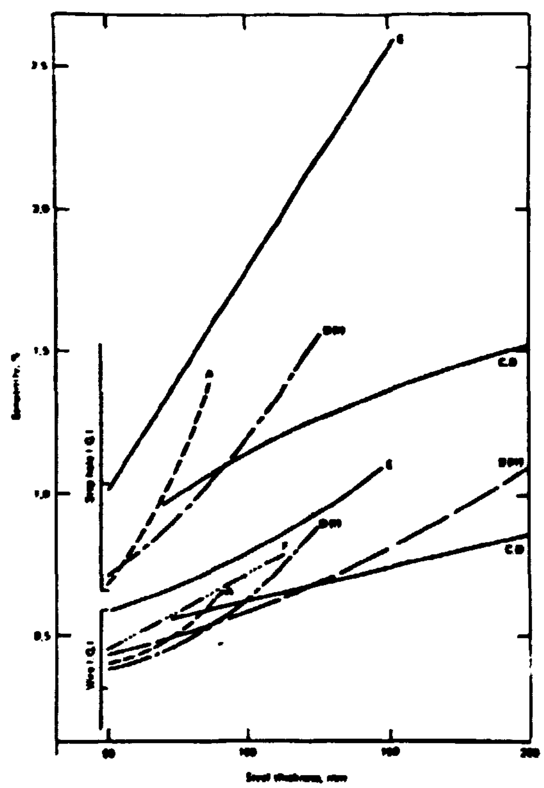


Fig. 56. IQI sensitivity values for different radiographic equipment.

11.4 Exposure charts and calculators

For gamma radiography, exposure charts are given in the form of the relation between the exposure Ci/h Ci.h at a certain distance as function of the thickness of the radiographed material. They are valid for a specific combination of intensifying screens and processing conditions, and for a certain film density (specified on the chart).

On fig. 57 an exposure chart for steel and Co-60 gamma

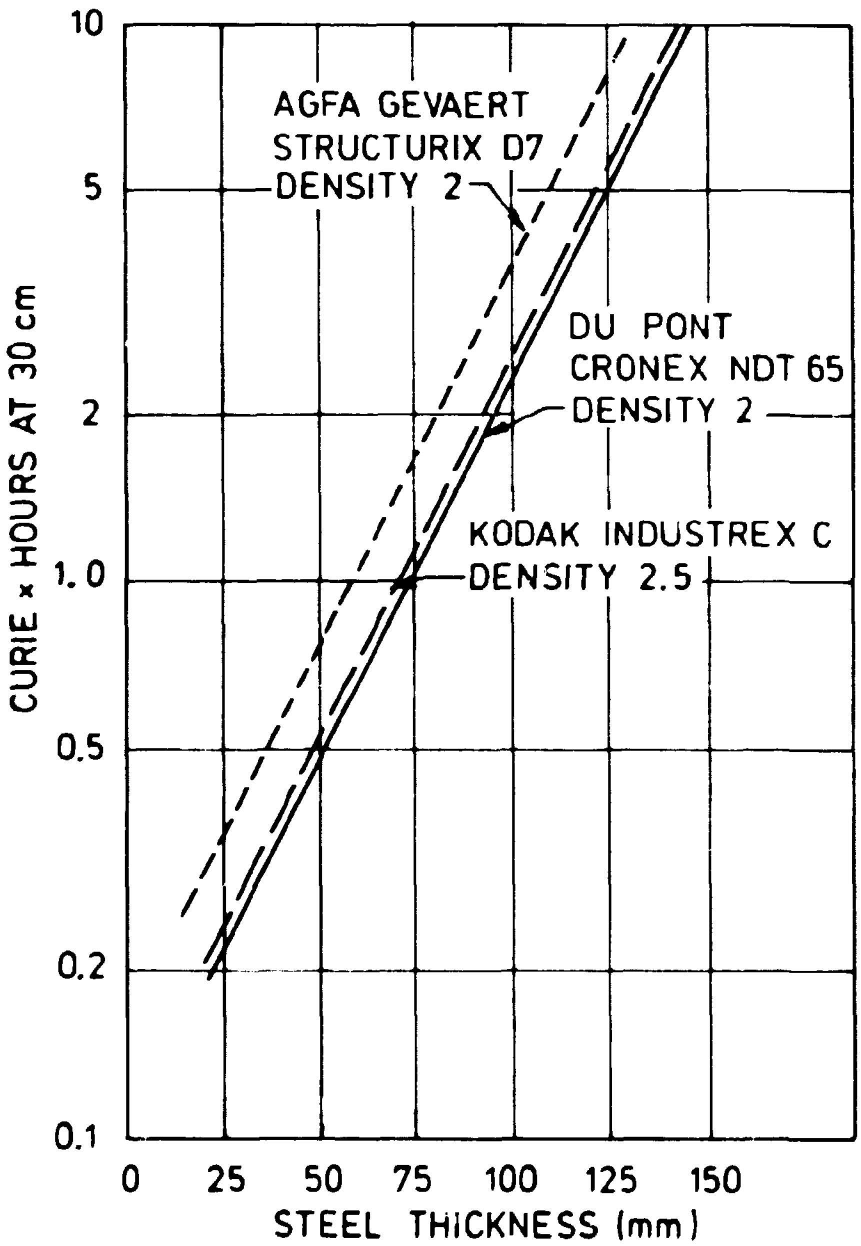


Fig. 57. CO 60 exposure chart for steel

radiation is given. Figs. 58 and 59 give similar exposure charts for Cs-137 and Ir-192 for steel, whereas fig. 60 gives an exposure chart for Al exposed with Tm 170. All those charts

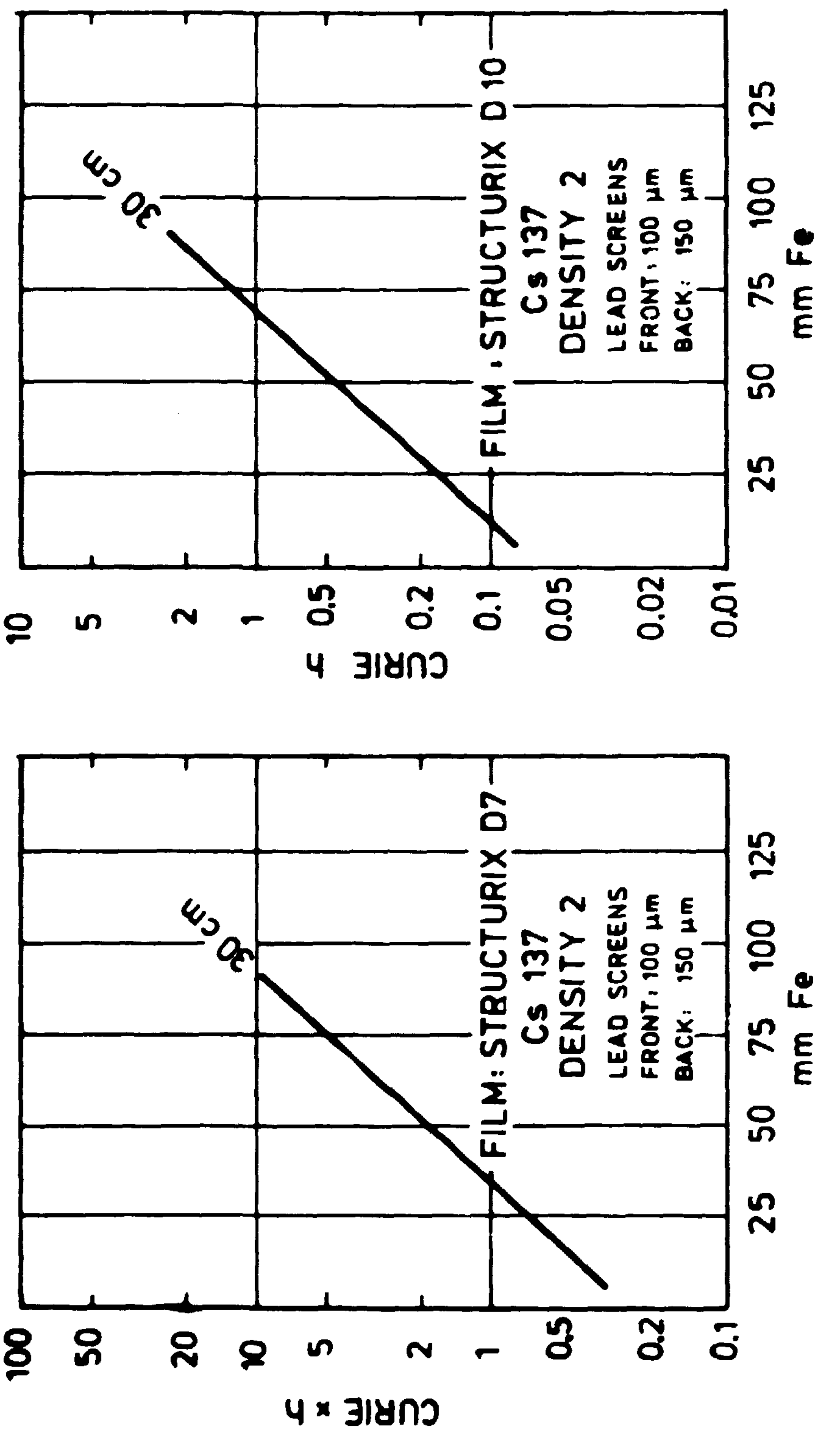


Fig. 58. Cs-137 exposure chart for steel

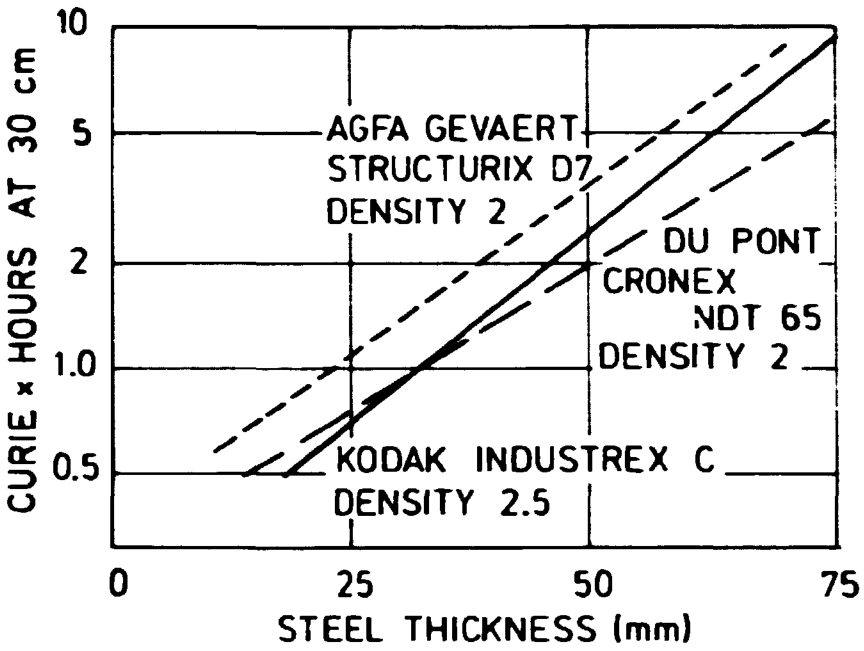


Fig. 59. Ir-192 exposure chart for steel

were prepared for a 30 cm FFD. For other distances, the exposure (in Ci/h) ought to be recalculated (according to the inverse square law of radiation intensity). E.g., for a FFD of 60 cm four times the layer exposures will be necessary for a 20 cm distance - 2.25 times shorter. All curves were given for film density D=2.

Instead of exposure charts, exposure calculators can be used. They are sometimes supplied by X-ray film manufacturers (see fig. 61).

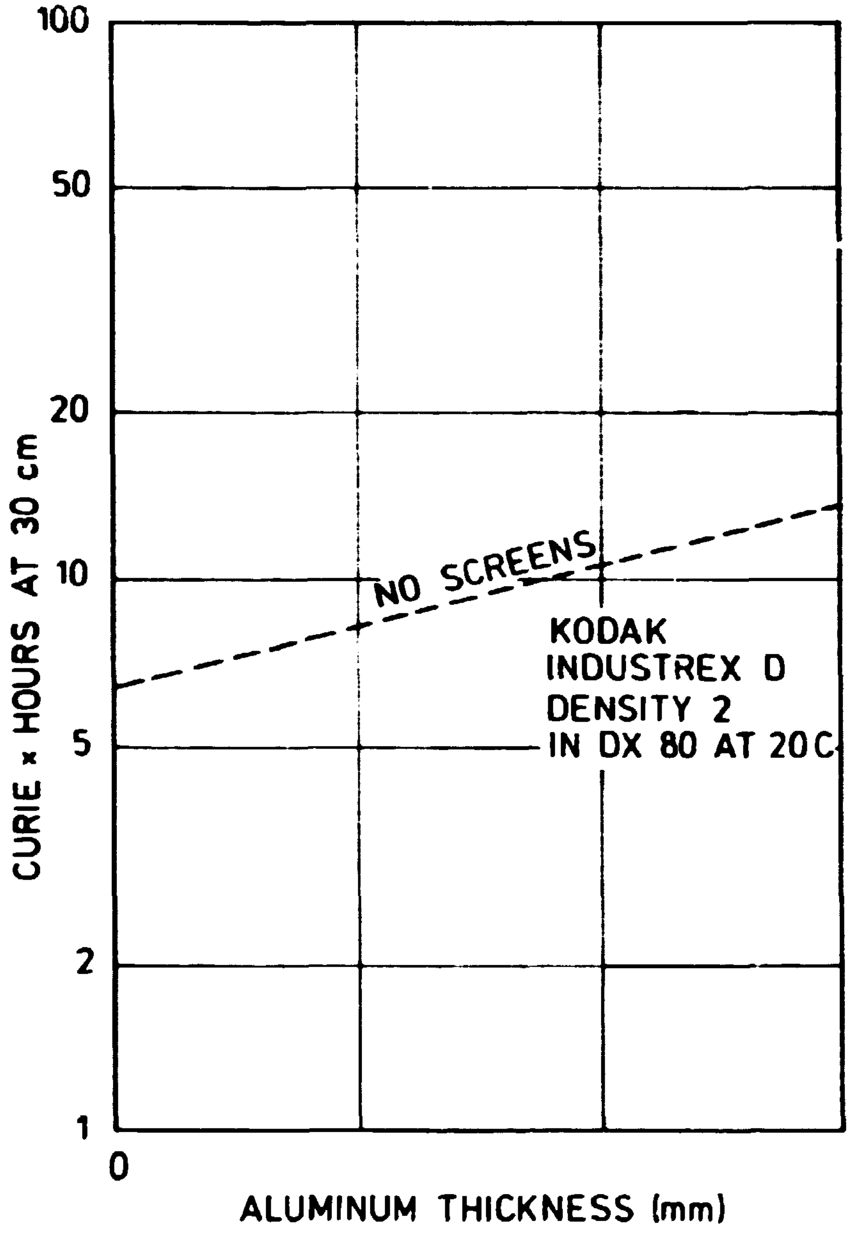


Fig. 60. Tm 170 exposure chart for aluminium

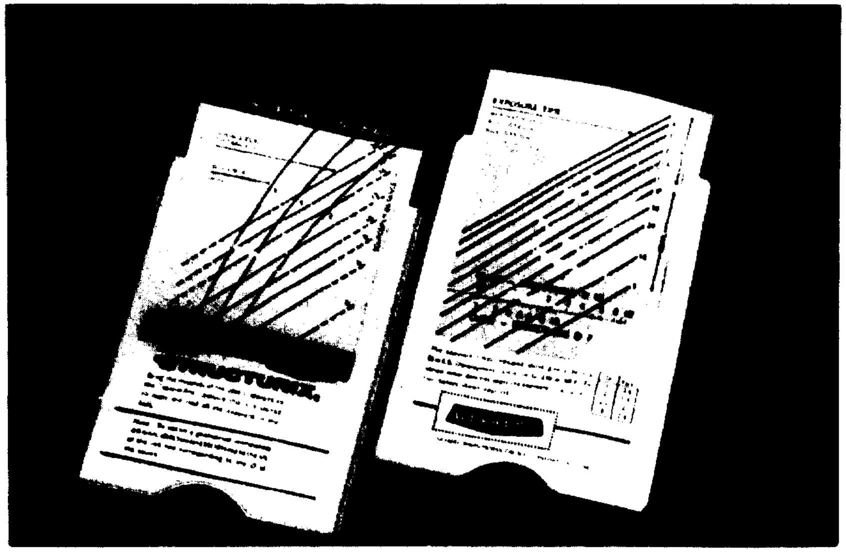


Fig. 61. Exposure calculator for gamma rays

12. DETECTS IN WELDS REVEALED BY RADIOGRAPHY

The defects which can be revealed by radiography in fusion welds have been classified by various international and national organisations.

The IIW Collection of Reference Radiographs of Welds consists of radiographs showing typical weld imperfections of different degrees of severity and is intended to serve as a guide for interpretation of radiographs. It is not considered as an acceptance standard for welds, but as a basis for comparison of radiographs as regards the nature and amount of any weld imperfections shown (see fig. 62).

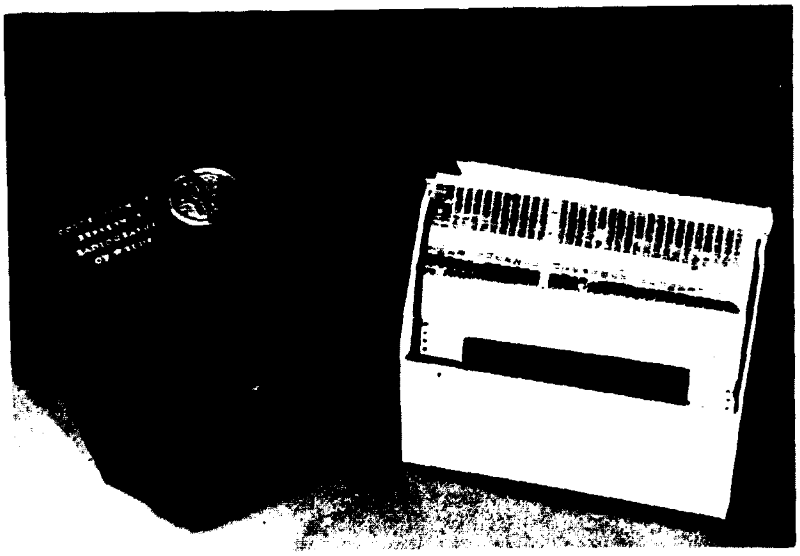


Fig. 62. IIW Collection of Reference Radiographs of Welds

In the IIW Collection of Reference Radiographs of metal arc butt welds in steel (within the limits of about 10 to 30 mm plate thickness) the radiographs have been divided into five groups taking into account the relative importance, so far as is known, of the different types of defects. The five groups, signified by colours, are described as follows:

Colour	The radiograph shows
Black	A homogeneous weld or a weld with a few small scattered gas cavities
Blue	Very slight deviations from homogeneity in the form of one or more of the following defects: gas cavities, slag inclusions, undercut.
Green	Slight deviations from homogeneity in the form of one or more of the following defects: gas cavities, slag inclusions, undercut, incomplete penetration.
Brown	Marked deviations from homogeneity in the form of one or more of the following defects: slag inclusions, undercut, incomplete penetration, lack of fusion.
Red	Gross deviations from homogeneity in the form of one or more of the following defects: gas cavities, slag inclusions, undercut, incomplete penetration, lack of fusion.

The defects shown have been characterised by the following code letters, provisionally adopted by IIW -Com. 5:

Term	Description	Radiographic apprearance
A. Gas cavities		
Aa - Porosity	Cavities due to entrapped gas. Elongated or tubular cavities due to entrapped gas.	Sharply defined dark shadows of rounded contour. Sharply defined dark shadows of rounded or elongated contour depending upon the orientation of the defects
B. Slag inclusions		
Ba - Of any shape and in	Slag or other foreign matmet entrapped during welding	dark shadows or irregular contour.
Bb - Slag lines	Elongated cavities containing slag or other foreign matter	Dark lines, more or less interrupted, parallel to the edges of the weld.
Bc - Weaving faults	Slag inclusions due to incorrect weaving technique during welding	
Bd - Fault from bad chipping	Slag inclusions caused by the use of an incorrectly shaped or worn chisel	Mostly two parallel dark lines with a sharp outline to the otside of the weld, and an irregular outline to the inside.
Bf - Fault at junction of seams		
C. Lack of fusion	Two-dimensional defect due to lack of union between weld metal and parent metal	Thin dark line with sharply defined edges. Depending upon the orientation of the defect with respect to the X-ray beam, the line may tend to be wavy and diffuse.
D. Incomplete penetration	Lack of fusion in the root of the weld or a gap left by failure of the weld metal to fill the root	Dark continuous or intermittent line in the middle of the weld
E. Cracks		
EA - longitudinal cracks	Discontinuity produced by fracture in the metal	Fine dark line, straight or wandering in direction
Eb - Transverse cracks		
F. Undercut	A groove or channel in the surface of the plate along the edge of the weld	A dark line, sometimes broad and diffuse, along the edge of the weld

Fig. 63 shows a card from the IIW Collection of Reference Radiographs of Welds on which all the information about the weld itself, the radiograpnic method and type of discontinuity and its degree is placed around the radiograph.

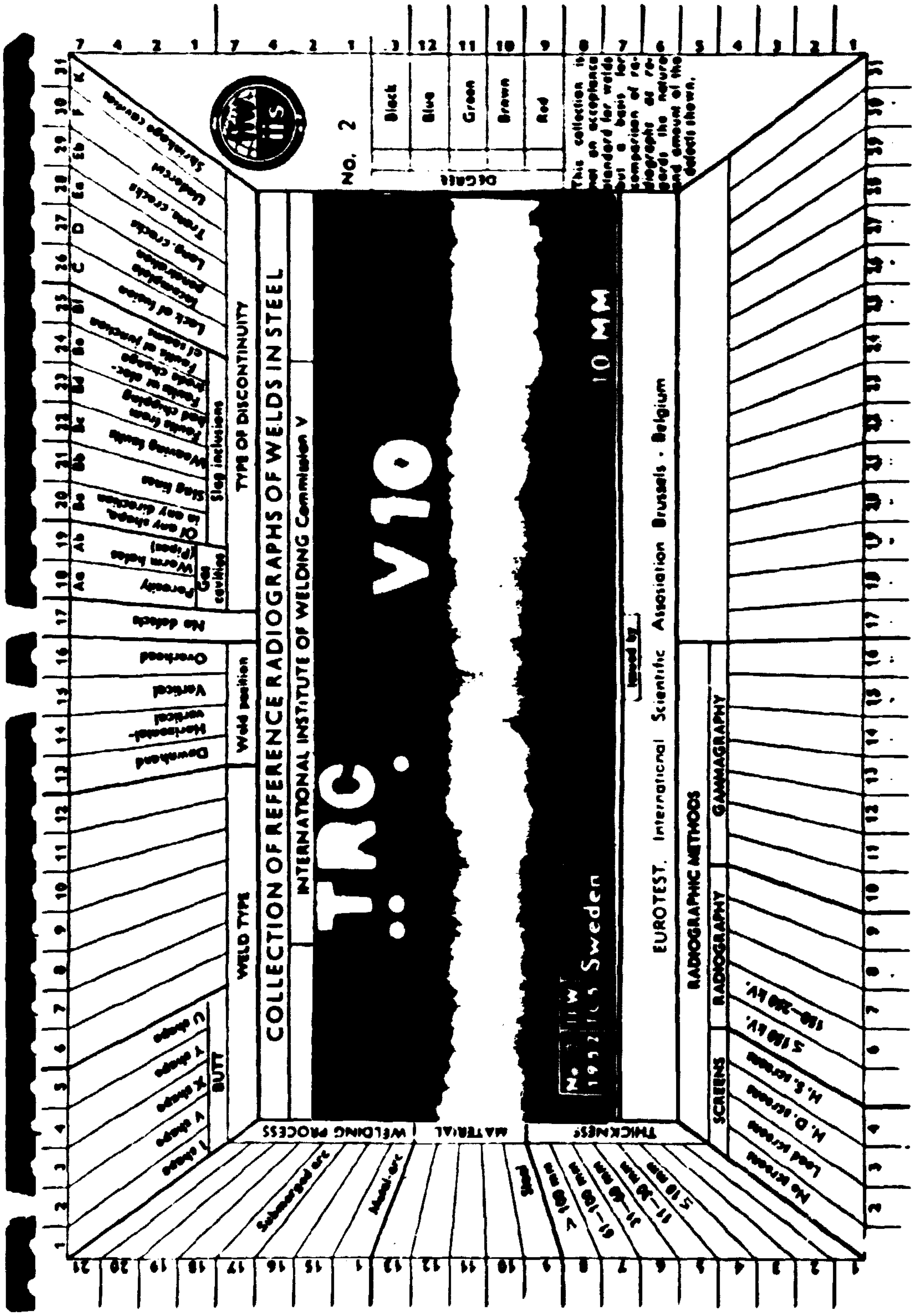


Fig. 63. A card from the IIW Collection of Reference Radiographs of Welds

In a separate publication "Radiographs of welds" prints or radiographs are given with the same description as shown in fig. 6´ . Moreover, drawings are included to make clear the position in the welds of the various defects shown on the radiographs.

In the IIW Collection of Reference Radiographs of Welds in Aluminium and Aluminium Alloys (plates with a thickness of 1 to 16 mm) the radiographs of butt welds have been divided into 5 groups, graded in accordance with the relative importance, as far as this is known, of the different types of defects. The 5 groups, signified by colours, are described as follows:

Colour	The radiograph shows
Black	A homogeneous weld or a weld with a few gas cavities or with scattered heavy metal inclusions
Blue	Very slight imperfections as regards homogeneity in the form of one of more of the following defects: gas cavities, heavy metal inclusions, flux inclusions, oxide inclusions, undercut.
Green	Slight imperfections as regards homogeneity in the form of one or more of the following defects: gas cavities, heavy metal inclusions, flux inclusions, oxide inclusions, undercut, incomplete penetration, shrinkage cavities
Brown	Marked imperfections as regards homogeneity in the form of one or more of the following defects: gas cavities, heavy metal inclusions, flux inclusions, oxide inclusions, undercut, incomplete penetration, lack of fusion, shrinkage cavities
Red	Gross imperfections as regards homogeneity in the form of one of more of the following defects: gas cavities, heavy metal inclusions, flux inclusions, oxide inclusions, undercut, incomplete penetration, lack of fusion, cracks, shrinkage cavities

The radiographs of spot welds have not been divided into such groups and are consequently not signified by colours.

The defects shown have been characterized by the following code letters, provisionally adopted by Commission V of the IIW.

Term	Description	Radiographic appearance
A. Gas cavities	Cavities due to entrapped gas	Sharply defined dark shadows
C. Lack of fusion	Two-dimensional defect due to lack of union between weld metal and parent metal or between runs	Thin dark line with sharply defined edges. Depending upon the orientation of the defect with respect to the X-ray beam, the line may tend to be wavy and diffuse
D. Incomplete penetration	Lack of fusion in the root of the weld or a gap left by failure of the weld metal to fill the root	Dark continuous or intermittent line in the middle of the weld metal to fill the root
E. Cracks Ea Longitudinal cracks Eb Transverse cracks Ec Crater cracks	Discontinuity produced by fracture in the metal	Fine dark line, straight or wandering in direction
F. Undercut	A groove or channel in the surface of the plate along the edge of the weld	A dark line, sometimes broad and diffuse along the edge of the weld
G. Flux inclusions	Inclusions due to insufficient cleaning between runs or bad welding conditions	Dark shadows or irregular contour
H. Heavy metal inclusions	Foreign metal inclusions from the electrode or from the support, which is necessary for the welding operation	Light shadows of sharply defined circular or irregular contour
J. Oxide inclusions	Inclusions due to insufficient cleaning between runs or bad welding conditions	Dark shadows of low intensity and of wavy or diffuse contour, depending upon the defect with respect to the X-ray beam

Term	Description	Radiographic appearance
K. Shrinkage cavities (crater pipes)	Cavities (often filled with oxide) caused on solidification of the weld metal after interrupting the arc	Dark shadows of irregular contour in the centre of the weld, mostly combined with small but not always visible cracks
L. Expulsion of metal	Base metal which due to improper choice of welding data has been melted and expelled from the proper weld area	Light shadows of irregular contour

Besides the IIW collection of Peference Radiographs of Welds, which is very widely used in Europe, several standard reference radiograph collections have been published by the ASTM in the USA.

The ASTM E-390 standard contains three volumes of reference radiographs, based on seven nominal weld thicknesses and applicable to the thickness ranges given below:

Illustration Thickness - mm	Base material thickness range mm
Vol I	
0.8	to and including 1.3
2.0	over 1.3 to and including 3.2
4.8	over 3.2 to and including 6.4
Vol II	
9.5	over 6.4 to and including 13
19	over 13 to and including 48
51	over 48 to and including 76
Vol III	
127	over 75 to and including 203

Each volume contains illustrations of representative graded and ungraded discontinuities. The table in E-390 lists the discontinuity types and severities illustrated for each thickness of base material. Each of the graded discontinuity types has five severity levels, 1 through 5 in order of increasing severity. The ungraded discontinuities are included for informational purposes.

Besides, ASTM E-390 gives a description of the discontinuities in welds.

13. DEFECTS IN CASTINGS REVEALED BY RADIOGRAPHY

As with welding, there are some defects which are common to most casting processes, for both metals and non-metals, and some special defects which are characteristic of particular metals or processes. Castings are made in an enormous range of sizes, from a few grams in weight to nearly 100 tons, and they vary in shape from simple to extremely complex forms. The names given to various casting defects vary considerably between different industries, different countries and even between different areas of the same country.

For the purpose of enabling the interpretation of casting radiographs to be understood, without ambiguity of terminology, by those interested in the radiographic inspection of castings, a British Standard Terminology of Internal Defects in Castings as Revealed by Radiography - BS 2737 - was issued in 1956. The aim was to select terms applicable to all metals normally used in castings. The defects listed have been classified into five groups of associated types. These are further divided into subgroups and specific defects. The precise classification of a given defect cannot, however, always be made from a radiograph alone, because the line of demarcation between various groups and subgroups may not be clearly marked. The radiologist's report should, where possible, refer to the specific defect type within any group; but where doubt arises, alternative possibilities should be stated.

An effect found in some radiographs, diffraction mottling, arises from purely crystallographic causes, and is included as a separate section. It is not to be regarded as a defect.

Surface markings also give radiographic images which appear similar to the indications of some internal defects. For this reason, when the radiograph is examined the surfaces of the casting should always be inspected.

The Industrial Radiology Department of the Electrotechnical Institute in Warsaw, Poland, published in 1965 an eight-language edition of an "Atlas of internal defects in castings revealed by radiography" (see fig. 64).

Fig. 64. Atlas of internal defects in castings revealed by radiography

This atlas contains a series of radiographic pictures of defects in cast iron and carbon steel castings arranged according to the classification given below. This classification is illustrated by various examples given in the atlas.

This atlas should not, however, be used as a basis for accepting or rejecting actual castings which give radiographic pictures of defects similar to those contained in this collection.

The assessment of the quality of a particular casting should be based on data contained in acceptance standards, in which radiographic examinations can also be evaluated.

The classification applied in this atlas forms an open system which makes possible further complementation of the collection with new examples of radiographs.

The radiographs contained in the atlas should not be regarded as standards from the point of view of radiographic techniques (density, contrast and sensitivity).

The radiographic pictures of internal defects in castings revealed by radiography have been grouped according to the following classification:

1. VOIDS

1.1. Cavities
1.2. Porosities
1.3. Blowholes
1.4. Air locks
1.5. Microporosities

2. INCLUSIONS

2.1. Slag and sand inclusions
2.2. Metal inclusions

3. LACK OF CONTINUITY

3.1. Cracks
3.2. Lack of fusion.

In the USA there have been extensive attempts to codify the interpretation of casting radiographs, particularly for steel castings, by the use of collections of reference radiographs. These have been issued by the ASTM and there are series for X-rays, gamma-rays and megavoltage X-rays for a range of steel thicknesses up to 12". In the medium-thickness collection, internal casting defects are divided into seven groups; sand and other inclusions, gas and blowholes, shrinkage, chaplets, chills and hot-tears and there are radiographs illustrating different degrees of severity - sometimes five degrees - of each. The intention is that these reference radiographs should be used as acceptance standards and there is guidance given on classes of castings according to the severity of service conditions; although this usage is controversial, the value of these sets of radiographs for interpretation purposes is obvious. No radiographic techniques are included with the films, but there is an assumption of a good technique.

There are the following ASTM Standard Reference Radiographs for Steel Castings:

- E 446 (replacing E 71) up to 51 mm in thickness (fig. 65)

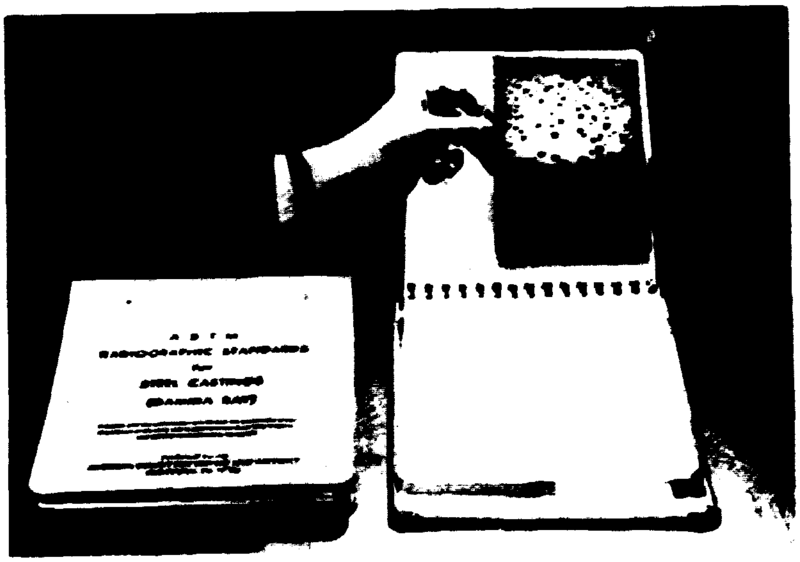


Fig. 65. ASTM E 446 Standard reference radiographs for steel castings up to 2 in thickness

- E 186 from 51 to 115 mm,
- E 280 from 115 to 305 mm (fig. 66).

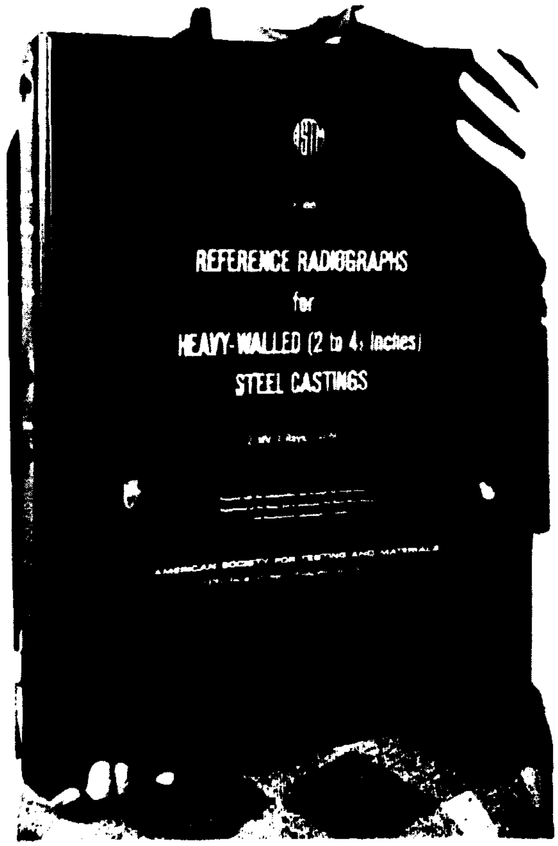


Fig. 66. ASTM E 280 Standard reference radiographs for heavy-walled (4½ to 12 in) steel castings

Each set of radiographs is for comparison only with the radiographs produced with equivalent radiation and consists of seven categories of discontinuities, in increasing severity levels, 1 through 5.

There are also several other collections of reference radiographs of castings from other materials (e.g. Al or Mg) or used for specific applications (e.g. aerospace industry).

14. RADIOGRAPHIC DARKROOM

Proper planning of the darkroom is essential to successful radiography. It is inconsistent to invest a great amount of money in efficient radiographic equipment and not to give due consideration to the provision of adequate space and apparatus for processing the films.

The darkroom should be designed to meet individual requirements, having regard to the amount and nature of the work likely to be undertaken. However, it will be found that by following certain basic principles, ease of working is attained and high photographic quality ensured.

The minimum requirements of an effectively planned darkroom are as follows:

1. The darkroom must be completely lightproof and should be properly screened from sources of X-rays or gamma-rays.
2. The room must be provided with adequate ventilation and heating for healthy and comfortable working conditions.
3. Running water (preferably hot as well as cold) and drainage must be available.
4. The darkroom must be dry and easy to clean frequently. It is inadvisable to locate darkrooms alongside an external wall which may be exposed to considerable sunshine. The room should, if possible, be sited for easy access from the radiographic workrooms, yet away from fumes such as might be emitted by chemical laboratories, coke ovens or similar sources of contaminating gases.
5. White light illumination should be sufficient. Lighting should be diffused to prevent heavily shadowed areas.
6. Equipment should be arranged to allow work to proceed in a logical sequence. Easy access to plumbing and other services will allow maintenance without moving fixed equipment.

7. Access to the darkroom should be possible without interrupting work and admitting white light.

It is preferable to restrict the radiographic department darkroom to the processing of X-ray films. In any case, the darkroom should not be smaller than 6 m^2 with a height of 2.5 m and larger rooms offer many advantages.

The darkroom should preferably be divided into a dry side and a wet side. The dry side will be used for loading and emptying cassettes, fitting films into developing frames and so on - in short, for all work where there must be no dampness. On the wet side, the films will be processed in the various tanks of chemical solution. For efficient working, and to ensure uniform quality, there should be automatic control of the temperature of the solutions.

As it is impossible to give precise recommendations about the exact layout of the darkroom, which must be adjusted to the specific space reserved for the darkroom in the whole radiographic laboratory, only an example of a layout will be given. Figure 67 gives such an example where a labyrinth entrance is used, and fig. 68 gives an example of a layout where a light lock (double doors) is used, as well as a pass box for film cassettes.

In figs. 67 and 68 examples are given of stationary darkrooms. However, for radiographic field work, such as e.g. pipeline control, transportable darkrooms are used. They are very often built into a motor vehicle (see fig. 69). Some portable film processing tanks are also available that can be transported together with other radiographic equipment and used on the spot in e.g. a field tent.

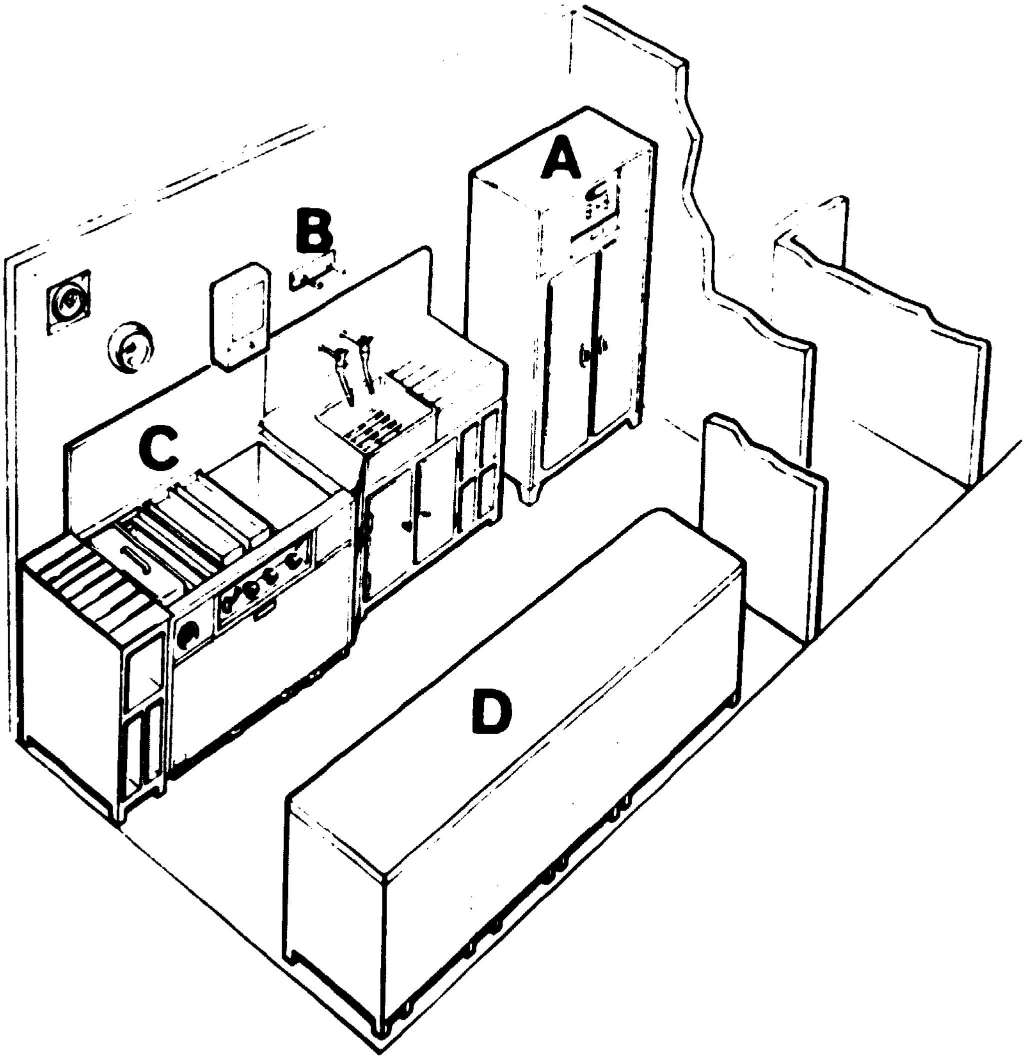


Fig. 67. Darkroom with a labyrinth entrance

A. Film dryer

B. F lm hanger rack and cassette box

C. Processing tanks

D. Dry bench

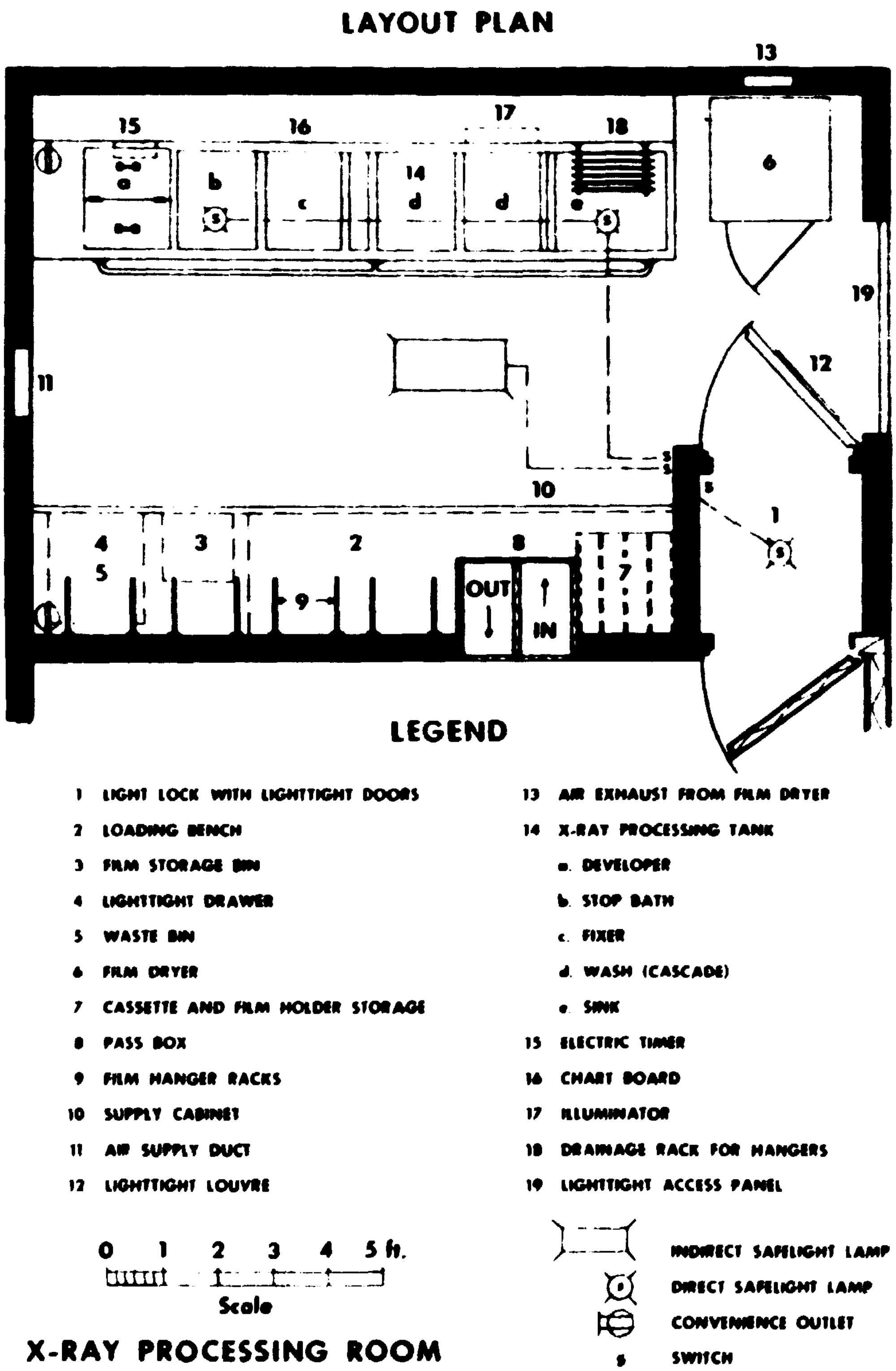


Fig. 68. Darkroom with a light lock and pass box

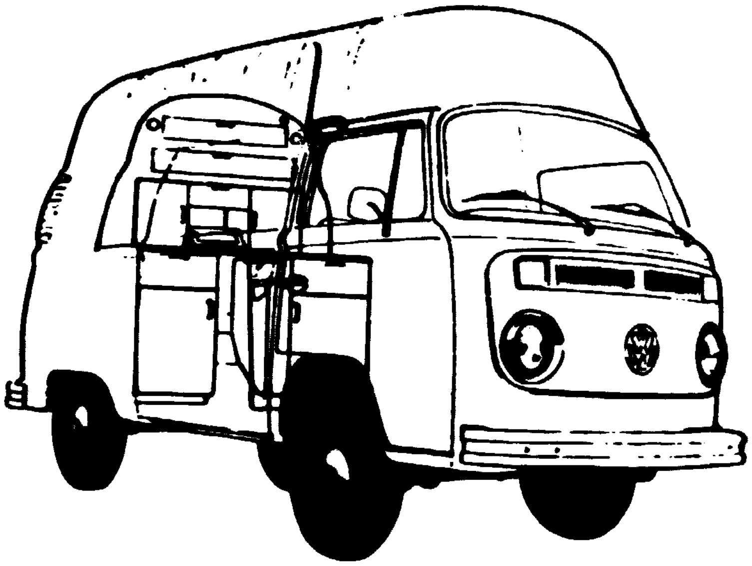


Fig. 69. Mobile darkroom

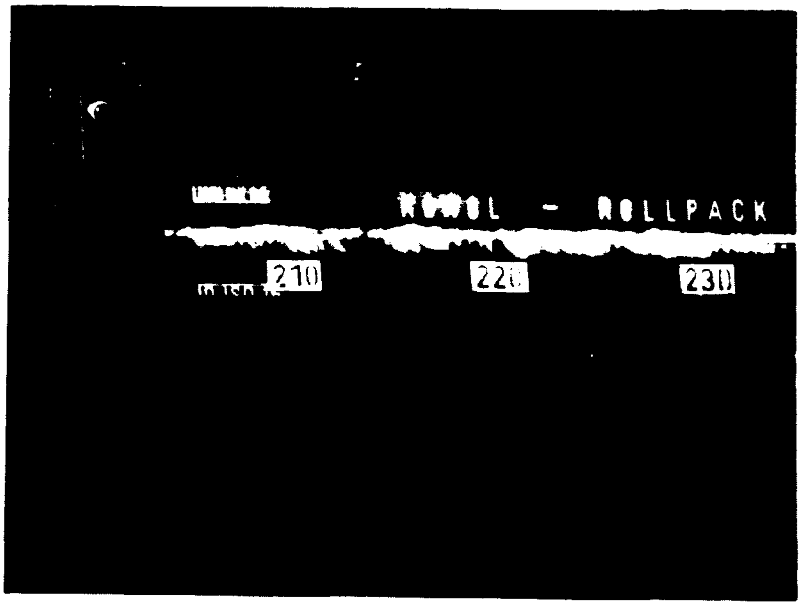
15. RADIOGRAPHIC ACCESSORIES

Besides the equipment shown in fig. 68, several other accessories are found in the radiographic darkroom. Among them are:

- Cassettes (rigid and flexible)
- Intensifying screens (lead, copper, fluorometallic)
- Film hangers (for film processing)
- Identification markers (letters and numbers)
- Cassette holders

and several other devices according to the specific radiographic jobs performed by the radiographic department.

Special illuminators are necessary for the interpretation of the radiographs (see fig. 70). It is essential that such an illuminator has adequate brightness to be able to interpret radiographs of high intensity (the ability to read radiographs of densities up to $D = 3.5$ or even $D = 4$ is essential). A good illuminator should furthermore have continuous control of its brightness. To avoid glare when films are changed on the illuminator, the illuminator has two brightness levels. The stand-by (low) level used during changing of films and the work brightness (controlled from the stand-by level to its maximum), which is usually switched on by a foot pedal.



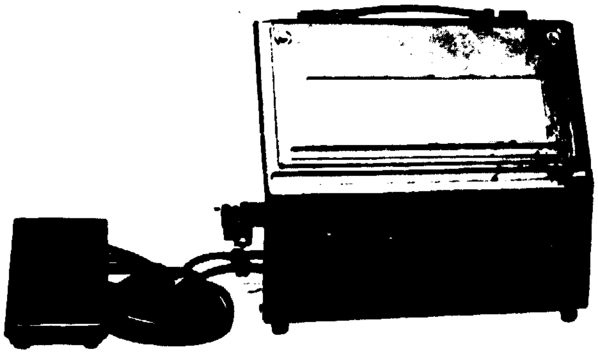


Fig. 70. Radiographic illuminator

Some details about the required viewing conditions for radiographic films are given in ISO 2504 International Standard.

16. NEUTRON RADIOGRAPHY

Neutron radiography employs thermal neutrons which at present are only available from a nuclear reactor, but portable neutron sources are under development. Its value lies in the differing opacities of various elements to neutrons, as compared with gamma or X-rays (fig. 71). Most striking is the way in which heavy metals such as tungsten and lead, which are relatively opaque to X-rays, are comparatively transparent to neutrons, whilst hydrogen (and its compounds such as water, petroleum derivatives, plastics, and explosives) is relatively opaque to neutrons, though transparent to X-rays. Thus neutron radiography can be used to detect the presence of a propellant in ammunition, or tiny quantities of petroleum grease or borax flux in metal assemblies, both of which tasks are impossible with gamma or X-rays.

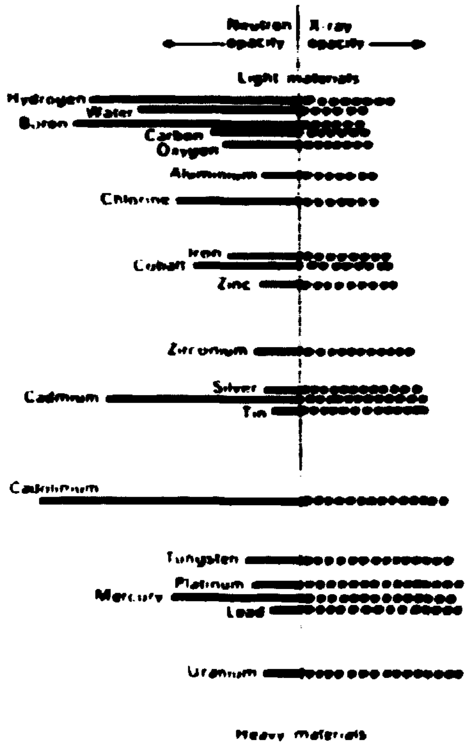


Fig. 71. Comparative opacity to thermal neutrons and 125 kV X-rays of some industrial materials

Of the three general types of neutron sources: accelerators, radioactive and nuclear reactors, only the last two can be practically used for neutronography. Here only the radioactive neutron sources will be shortly reviewed. The two important reactions in radioactive neutron sources are (α, n) and (γ, n) reactions. The highest output of (α, n) or (γ, n) sources listed in catalogues is 2.10^7 n/s per Ci.

As a higher output is required for neutronography, it can be seen that very large activities will be necessary.

Of all the radioisotope neutron sources, only one is suitable for practical neutronography. This is the Califorium-252 neutron source. The ^{252}Cf source emits neutrons by spontaneous fission at a rate of 2.3×10^9 n/s per mg. Its properties are such that high intensity neutron sources of small physical size can be made with relatively little associated gamma radiation.

The properties of ^{252}Cf are the following:

- mode of decay	-	alpha emission 96.9%	
	-	spontaneous fission 3.1%	
- Half-life	-	alpha decay	2.73 years
	-	spontaneous fission	85.5 years
	-	effective	2.65 years
- neutron emission	-	2.3×10^9n/s mg	
	-	4.3×10^9 n/s Ci	
- specific activity	-	536 mCi/m g	

The neutron radiation from ^{252}Cf consists principally of neutrons from spontaneous fission. A very minor contribution arises from (α, n) reactions with light elements such as oxygen.

Neutron sources are made as capsules (see fig. 72) in which ^{252}Cf oxide is contained. The maximum content of the source is 1 mg or 536 mCi with a neutron emission of 2.3×10^9 n/s.

There are a number of methods for photographically detecting neutrons. Among these are the use of special emulsions loaded with neutron absorbers and normal photographic materials both by themselves and with various converter screens. The loaded emulsion technique (usually loaded with materials such as boron or lithium) and the use of normal X-ray films by themselves are relatively slow neutron detection methods which, although useful in many areas, have had little application in radiography.

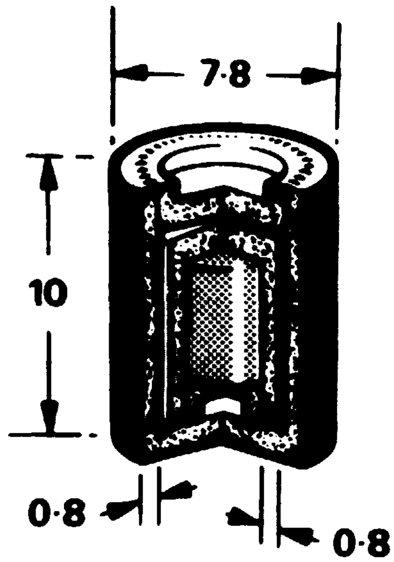


Fig. 72. Encapsulated Cf 252 neutron source

The photographic detection method used for neutron radiography has employed conventional X-ray film used with converter screens. These screens convert the neutron image into one which can be detected more readily by the X-ray film. This detection method for neutrons has been used not only for radiography but also for neutron diffraction, dosimetry, and other applications.

In the converter screen technique the neutron image is changed into one of alpha, beta or gamma radiation and is thereby photographically more detectable than the unconverted neutron image. The speed factor by which the detection process can be improved is in the order of 50 to 100 times.

These converter materials are essentially of two different types, potentially radioactive materials and prompt emission materials. The latter materials, characterized by lithium, boron, cadmium and gadolinium, have little tendency to become radioactive but do emit radiation immediately upon the absorption of a neutron. This type of converter screen must be used in what has been termed a direct exposure method for detecting neutron images. That is, the film and screen must be exposed together to the neutron image in order that the film may be present to detect the prompt radiation emitted from the screen. This direct exposure method is a fast detection technique. It does have the disadvantage, however, that the film is able to detect other interfering radiation, such as gamma radiation in the neutron beam, or that which may be emitted by scattered radiation from the object or from other objects in the beam path.

This disadvantage can be overcome by using a detection method called the transfer technique. In this method, the film is not exposed to the neutron imaging beam at all. The image is detected by a potentially radioactive screen. This detecting screen, which becomes radioactive proportional to the neutron intensity at each point of the image, can then be placed next to photographic film at a location remote from the neutron beam and allowed to decay. The radioactive emission of the screen, which will be relatively uninfluenced by interfering gamma radiation in the neutron imaging beam, then exposes the film. This technique is usually slower then the direct exposure method but does have the significant advantage of being uninfluenced by much of the interfering radiation that can be present in the neutron imaging beam.

On fig. 73 the direct and transfer methods of neutron radiography are shown using conventional radiographic film and neutron image converters. At the bottom of fig. 73 the loaded emulsion (called also track-etch technique) technique is shown. The nitrocellulose film used for this purpose can be used in daylight, as it is not sensitive to visible light.

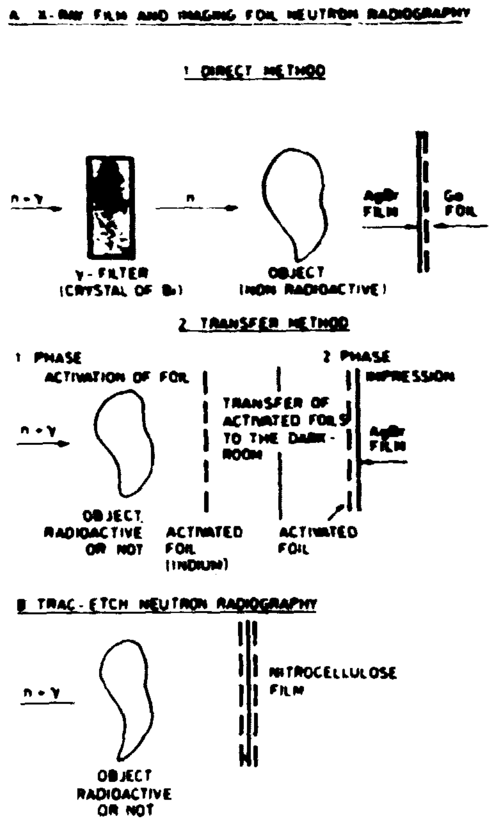
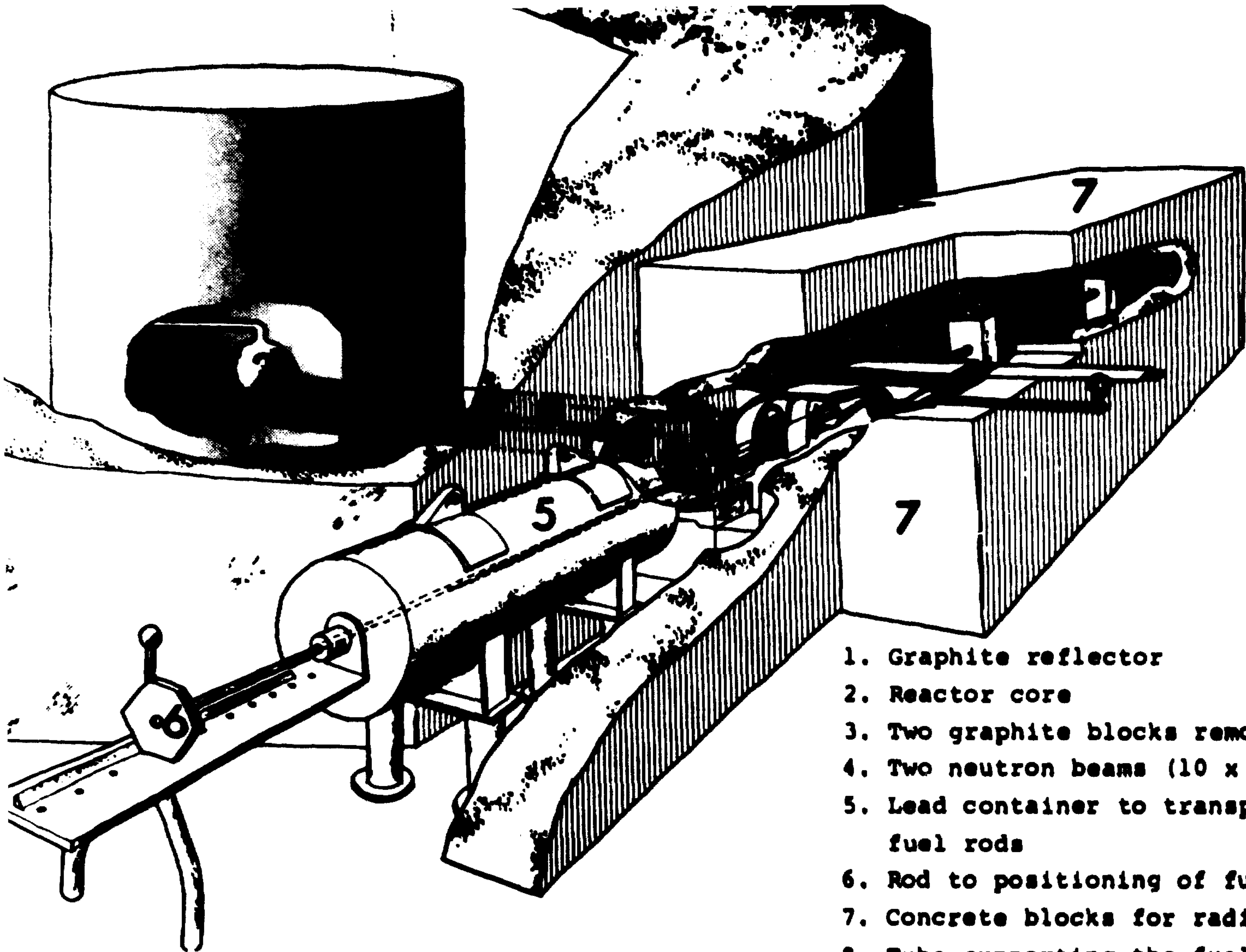


Fig. 73. Neutron radiographic techniques

A practical arrangement for neutron radiography using a double beam of thermal neutrons from a reactor and the transfer technique with a 0.1 mm Dysprosiüm foil and X-ray film is shown on fig. 74.



1. Graphite reflector
2. Reactor core
3. Two graphite blocks removed
4. Two neutron beams (10 x 10 cm)
5. Lead container to transport and handling of irradiated fuel rods
6. Rod to positioning of fuel rod during radiography
7. Concrete blocks for radiation shielding
8. Tube supporting the fuel rod
9. Mecanism for introduction of imaging foils behind the fuel rod to be radiographed

Fig. 74. Neutron radiography arrangement using thermal neutrons from a reactor and the transfer technique

17. RADIOMETRIC NDT

Of the three radiologic methods of NDT, radiography is so far the most widely used. Fluoroscopy is restricted to X-rays. The third metho - radiometry - is used with both X- and gamma--rays.

The principle of this method (shown on fig. 75) consists of the following: a gamma-ray beam from a radiation source

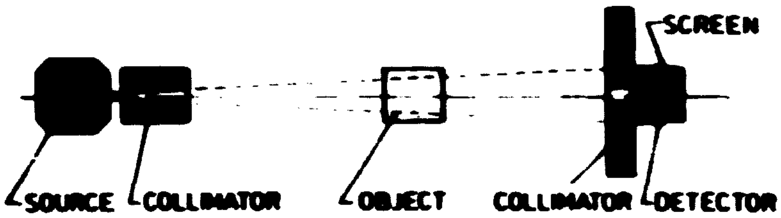


Fig. 75. Principle of radiometry

enclosed in a container is collimated by a collimator placed in front of the source container. The object to be examined is placed in this narrow radiation beam which, after leaving the object, reaches a radiation detector through a second collimator placed in front of it. The source-side collimator serves mainly to limit the size of the beam and the detector-side collimator serves mainly to protect the detector from scattered radiation produced in the object.

Scintillation counters are generally used as radiation detectors, as they show best sensitivity and resolution. The output of the scintillation counter is fed into an exposure-rate meter and recorder.

The scintillation counter measures the intensity of radiation passing through the object. Changes of this intensity can be due not only to the presence of internal defects but also to the changes in thickness, or density of the material.

Usually the object under examination moves a· oss the radiation beam. Thus a scanning is performed, gi·ing a continuous measurement along the scanning bath. Usually, several scanning traces are used for the same object.

The radiometric method is applied to the NDT control of various products, e.g. in steel production to control the rolling process of hot steel blooms. Another example of the radiometric method is the quality control of graphite electrodes (400 x 400 x 1100 mm) are controlled using a 8.5 Ci ^{137}Cs source and scintillation counter. The scanning is shown schematically on fig. 76. Figure 77 shows a picture of a graphite electrode on which the scanning paths (at 20 mm distance) are shown.

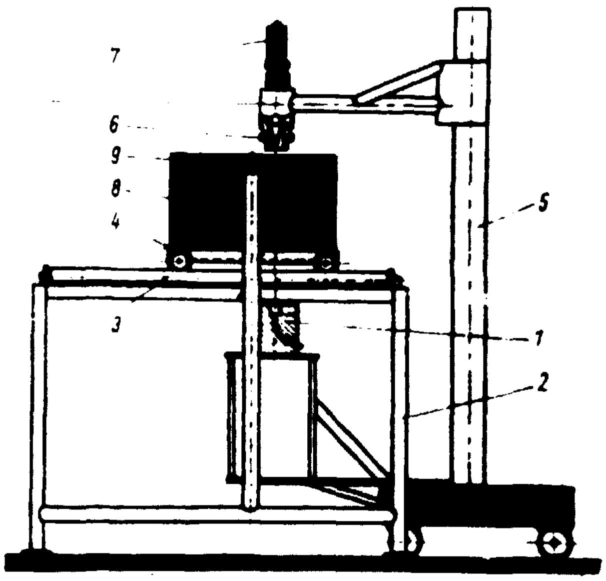


Fig. 76. Radiometric scanning of graphite electrodes

1. Lead container
2. Scanning table
3. Lower carriage
4. Upper carriage
5. Scintillation probe holder
6. Collimator at the scintillation counter
7. Scintillation probe
8. Graphite electrode
9. Driving mecanism

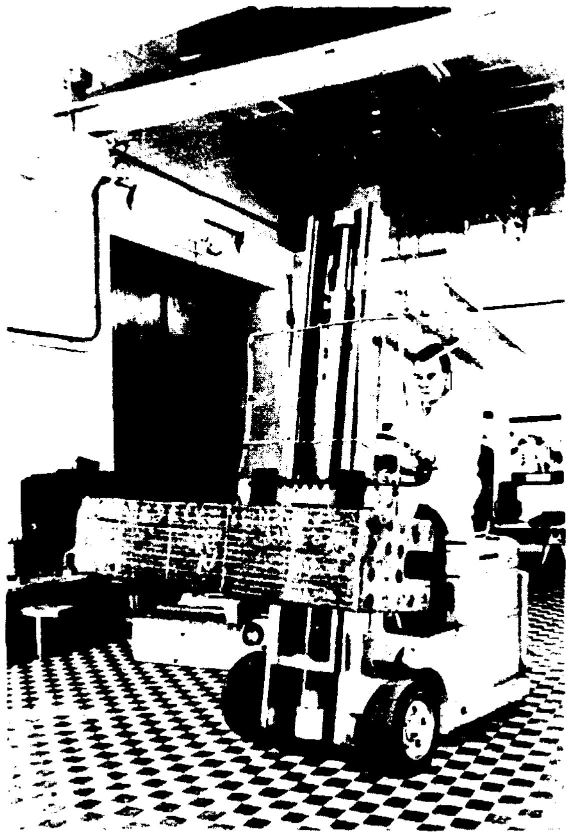


Fig. 77. Graphite electrodes with scanning marks

Another example of the application of the radiometric method is the quality control of grinding wheels. Here an Americium-241 gamma-ray source is used (emitting low energy, 0.06 MeV gamma-rays) which, after passing the grinding wheel (rotating on a turn table), reached a scintillation counter. The radiometric arrangement is shown on fig. 78.

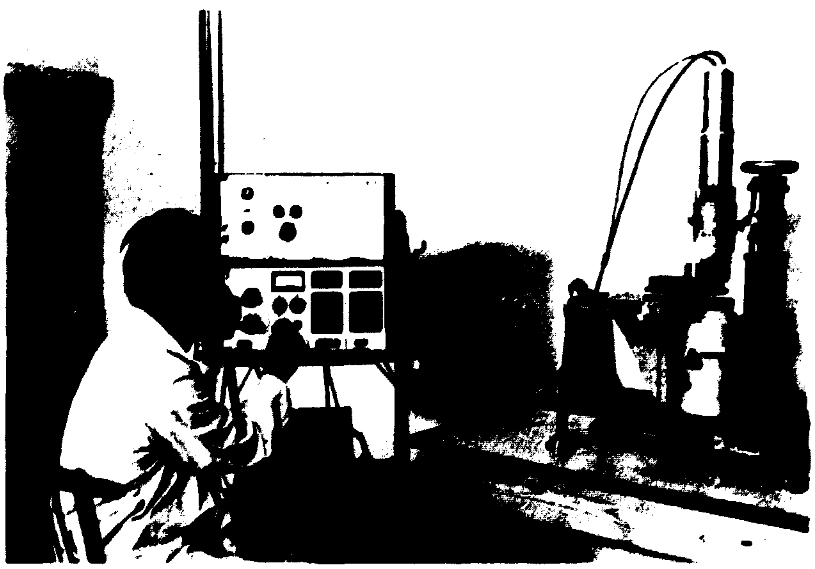


Fig. 78. Radiometric examination of grinding wheels

18. COST OF THE EQUIPMENT

To give some idea of the economic side of radiographic NDT, the prices of gamma-ray sources, gamma radiography machines and radiographic accessories are given below. There is such a variety of different types of equipment that it is impossible to give a full review of the cost. The prices vary also from manufacturer to manufacturer, as well as from country to country.

The prices quoted below are based on quotations given by European manufacturers at the end of 1976. They are neither complete nor exact, and are quoted just to give a general idea of the cost of radiographic NDT equipment. (All prices are quoted in US dollars).

18.1. Radiation sources

Table 14 gives the prices of some most frequently used sources for gamma-radiography (different sizes and activities).

Table 14. Prices of gamma-radiography sources

Radioisotope	Dimensions of active part dia. x length mm	Maximum equivalent activity Ci	Price US $
Cobalt,Co-60	1x1 2x2 3x3 4x4	1 6 20 100	130 170 275 990
Caesium,Cs-137	3 6x2	0.3 3	140 265
Iridium,Ir-192	0.5x0.5 1x1 1.3x1.3 2x2 3x3 4x4	1 6.7 12 40 110 200	105 135 160 295 630 1065
Thulium,Tm-170	0.5x0.5 1x1 2x2 3x3	1 5 15 35	335 335 335 375

18.2. Gamma radiography machines

The prices quoted below are given for the projection type gamma radiography machines as those are most commonly used in practice. Table 15 quotes the prices according to the type of radiation source used in the machine.

Table 15. Gamma radiography machines-prices

Radiation source		Exposure container		Price	Remarks
Radioisotope	Activity Ci	Shielding material	Weight kg	US $	
Ir-192	40	U	12	3500	Differences in weights and prices quoted for exposure containers with the same activity are due to quotations originating from different equipment manufacturers.
	85	U	12	3100	
	100	U	15	3950	
	100	U	20	4100	
	160	U	15	3400	
	200	U	18	5000	
Co-60	10	U	95	9700	
	10	U	102	8000	
	30	U	120	11000	
	30	U	136	10000	
	100	U	140	13800	
	100	U	184	11700	
	250	U	250	22000	
Yb-169	5	U	1.9	2300	
Ir-192	20	U	30	22000	Pipeline Crawler
	100	U	75	24500	Pipeline Crawler

The prices given above do not include the cost of radioisotopes. Neither do they include the auxiliary equipment (such as collimators, exposure heads, exposure head stands). Therefore one must remember that the prices must be increased by 10 to 20 % to include the auxiliary equipment necessary for radiographic work.

It is interesting to compare the prices of gamma-radiography machines with those of the X-ray machines that are most commonly used for radiography.

Table 16 quotes the prices of some X-ray machines (without accessories).

Table 16. Prices of portable X-ray machines

Maximum rating		Weight of the X-ray head	Price US $
kV	mA	kg	
160	5	30	7700
200	8	45	8700
250	8	70	10300
300	6	100	12300

18.3. Radiographic darkroom

In table 17 prices are quoted for the equipment necessary to process the X-ray films as well as for many fo the accessories necessary to perform radiographic work.

Table 17. Prices of radiographic darkroom equipment and accessories

Item	Destination	Price in US $
Processing tanks (stationary)	Films up to 10x48 and 30x40 cm	2600
Processing tanks (mobile)	10 films 10x48 or 30x40 cm	750
Processing tanks (transportable)	24 films 10x48 cm	1500
Film dryer	60 films 10x48 cm	700
Transportable, complete processing set (with dryer)	24 films 10x48 per hour	1500
Flexible cassettes	Set of 10x24, 10x48 and 30x40 cm; 6 each	100
Rigid cassette	Set of 10x24, 10x48 and 30x40 cm; 3 each	370
Intensifying screens	Set of 10x24, 10x48 and 30x40 cm; 10 each	100
Lead markers	2 sets of letters and numbers	80
Cassette holders	2 sets for cassettes 10x24 and 10x48 cm	100
IQI's	3 sets for Fe, Al and Cu	125
Film hangers	6 sets for 10x24, 10x48 and 30x40 cm films	175
Illuminator	For 10x48 cm films	600
Illuminator	For 30x40 cm films	900
X-ray films	10x24 cm box of 75	35
X-ray films	10x48 cm-box of 75	65
X-ray films	30x40 cm-box of 75	170

Item	Destination	Price in US$
Processing solution	Dispensable after ca. 1 month's use	125
Radiation monitor	For radiation protection measurements	500
Personal dosimeters	Sets of 6, with loading and reading equipment	500
Darkroom lamp	Set of 3	150

ACKNOWLEDGEMENT

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